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V. M. Sheynin and V. I. Kozlovskiy

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16. Abstract The work deals with contemporary problems of passenger aircraft design, tracing tendencies from the past through the present, and presenting forecasts for the future. Problems are approached primarily from the standpoint of increasing economic effectiveness, with a goal of improving passenger-cargo mixes, operating expenses and thresholds of profitability. The work goes into problems of different configurations with respect to engine placement, advantages of different types of engines, empennage configuration, layout of passenger and cargo space and thrust- and lift-to-weight-ratios, but does not go deeply into technical aspects of actual engineering solutions. The most attention is paid to standard jet passenger airplanes and airbuses, but Short TakeOff and Landing (STOL) and Vertical TakeOff and Landing (VTOL) airplanes are also discussed with respect to their use in relatively undeveloped areas.

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Annotation

Problems of Designing Passenger Aircraft, V. M. Sheynin and V. I. Kozlovskiy, Moscow, "Mashinstroyeniye" Press, 1972, 308 pages.

Contemporary problems of designing, combined with the overall idea of increasing the technical and economic effectiveness of airplanes and the transport sytem in total are reviewed in the book. It will familiarize readers with basic tendencies in the development of jet passenger aviation in the past and with forecasts for its development in the coming decade.

The book is recommended for science workers and a wide circle of specialists in the aviation industry and in the civilian air fleet. It will be useful for instructors and students of aviation learning institutions.

24 tables, 133 illustrations, bibliography, 96 entries.

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Foreword

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With the introduction of third generation subsonic passenger airplanes and supersonic passenger airplanes into operation, a great quantitative and qualitative leap is taking place in the development of aviation, as the result of which the air fleet will, by the 1980's, occupy the first place among the remaining forms of transportation as it relates the carrying passengers. This leap will be made possible by a sharp increase in the dimensions of the airplane and in the speed of flight. Meanwhile, subsonic airplanes will remain the major form of air transport for many years to come.

In the creation period for new types of passenger airplanes (the air bus is presently one of these), many scientific and technical problems usually arise. Discussions on the search for optimal solutions and on the most expedient appearance of the future airplane are ongoing in the periodical press. All of this is reflected in this book. In it is given a developed analysis of the most urgent problems which led to an interesting correlation and practically useful conclusions. Some of the positions, naturally, may prove to be controversial.

The digression into the plan of analyzing the basic tendencies in the development of aviation precedes a review of the fundamental questions of the work, since creative activity by the aeronautical designer is unthinkable without a clear understanding of the interrelationship between theory and engineering practice, which can be obtained on the basis of studying the history of science and technology.

The chapter in which questions of modifications, having exclusive significance in our time, are studied, serves as an organic continuation and connecting link between questions of history and contemporary problems. Without solving this problem in the process of designing airplanes, the general technical and economic problem cannot be solved. Many tasks in the design of contemporary passenger airplanes are analyzed from all sides in this book.

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Concrete paths to the solution of certain problems are not supported in this work and the authors avoid various recommendations. This, if you please, is correct. In the process of the stormy development of aviation, much ages rapidly and therefore the authors limited themselves to an analysis of the paths indicating the fact that solution is possible but is in every case connected with concrete conditions. The second direction of the book consists of an analysis of the principles of aviation development and the interrelationships between basic characteristics and parameters of an airplane. Their graphic expression

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is a descriptive illustration, and the interpretation in every case of a physical sense is totally pursuasive. It is evident from the large number of testimonials that the books of Laureate of the Lenin Prize V. N. Sheynin are widely and willingly used by specialists. It can be expected that this work will also enjoy a wide circle of readers.

General Aeronautical Designer, Academician S. V. Il'yushin

Authors' Foreword

The last period in the development of passenger aviation is istinguished by the creation of airplanes with the successive and, at this time, an especially significant increase in their scale (tonnage), and by new prinicples in the development of designs and by new design methods.

Contrary to the previous approach to design, which was limited to the development of only one variation of an airplane with set characteristics, contemporary principles propose the development of an entire family of modifications, the planning of further development of the airplane, widespread usage of standardization and specialization in equipment systems and structure types. All this determines the overall striving for creation of a flying apparatus with harmonic concentration of parameters and characteristics which is effective in all respects.

Contemporary methods of design are based on widespread and total economic studies, including economic evalution not only of the major solutions designed and executed, but also of the slight increases in weight, resistance, labor consumption and so forth. Economic studies are carried out on all stages of planning, beginning with the pre-drawing project and ending with the working drawings. /5 In this manner, the process of designing new equipment has in essence been transformed from a purely technical one into a technical-economic one. Technical calculations and economic investigations appear at the present time as equal elements, and the acceptance of design decisions is based upon the determination of costs.

Contemporary methods of designing make use of the achievements of cybernetics, reliability, technical esthetics, engineering psychology and so forth. The role of scientific prognosis and theoretic analysis grows constantly. The maximum utilization of computer technology allows rejection of a large number of disconnected approximations and semiempirical theories. A redistribution of time frames in creation stages of an airplane has also occurred: preliminary study, and the volume of wind tunnel and flight testing have increased, while at the same time

there has been a decrease in the period of planning and construction tasks and the overall period for creation of the airplane, which in the past had a stubborn tendency toward periodic growth.

The purpose of this book is to add to and develop some positions of works which shed light on airplane design [3, 18, 42, 59, 62, 95], especially in that part which touches on the design objective itself. The major task of those works was to present and develop engineering methods for determining the various parameters and characteristics of airplanes, and in this book the authors made an attempt to analyze the essence of the problem of design, attempting to reveal their contents and conflicts, substantiate their meaning and the reasons for their appearance and show the spasmodic character of the development of aviation. The basic tendencies in the development of airplanes and air transport systems illustrating solution of a number of aviation problems and new methods of airplane design are also traced in this work. Many of the problems reviewed here are without a doubt controversial and do not have, at least at the present time, well-defined solutions. If this work serves as a guide to consideration and further evaluation of these problems or to a review of a number of design tasks in a new plane, the authors will consider their assigned task to be fulfilled.

The study of all of the questions touched on in this work is based on experience in passenger aviation from the 1960's and prognoses of its development. Of domestic airplanes, passenger types were reviewed, and their study was made easier by the systematized data and results of a number of analyses published in the works of O. K. Antonov (1, 2), S. M. Yeger (18, 19), S. V. Il'yushin (22, 23), M. M. Kulik (35), A. N. Tupolev (54, 55) and A. S. Yakovlev (69).

The statements and conclusions presented in the work are based on investigations of the authors, on their personal representations and assertions (with the exception of those places where references to other works are given), i.e. no name is given here of a firm in the work of which they participated. /6

The text, up to Part V was written by candidate of technical sciences V. M. Sheynin, and Parts V-VII were written by candidate of economic sciences V. I. Kozlovskiy.

The authors express thanks to candidates of technical sciences V. F. Eroshin and V. I. Tolmachev, who took upon themselves the task of reviewing the book, and to other technical scientist Professor A. A. Badyagin, who gave much valuable advice upon reviewing the manuscript. The authors also thank their co-workers who rendered aid in the development of statistical material.

Introduction

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In the development of many types of equipment, particularly aviation equipment, it is possible to differentiate three stages and arbitrarily call them the origination, becoming and perfection stages. They are organically connected together and do not have defined orders in time, but each has its own characteristic primary directions and its known problems. Thus, in the first stage, the central problem was the practical achievement of flight itself. All the rest was solved only in the scale necessary for solution of that problem. The second stage was distinguished by a striving for achievement of acceptable values for the basic characteristics. The third is the stage of analysis and comprehension of the experience accumulated and its use in increasing all forms of airplane effectiveness. Subsequently, the first of these development stages named was the stage of the appearance of qualitative new phenomena in technology, the second was the stage of their quantitative but elementary growth, and the third was the stage of a relatively systematic increase in technical perfection. In terms of time, this one is the longest.

In the various periods of the last stage, certain basic and defined problems stand out from the large number of those solved. Each in their own time, for instance, these were the problems of strength (vibration and fatigue), and later that of the heat barrier; problems of increasing power unit thrust and perfecting airplane aerodynamics (the sound barrier); and engineering problems (monolithic large-dimension panels, honeycomb and other constructions). All these problems are not exhausted and their study continues, but they are basically solved, although to different degrees. For the contemporary stage of development, the major and decisive problems are those of the technical and economical effectiveness of passenger airplanes. Their acuteness is particularly connected to the increase in design complexity, the significant increase in the scope of intricate equipment complexes and, as a result, the extremely high expenses on planning, all-out testing, production and operation of this equipment. /8 Suffice it to say that the cost of 1 kg of an empty subsonic passenger airplane has risen by approximately a factor of 6 in the last 20 years and, with respect to supersonic aircraft, it has risen by a factor of 10.

Generally speaking, problems which are new in principle rarely arise in aviation development; more often, problems which are already known and, it would seem already solved, achieve a definite acuteness and require principally new solutions. In a number of cases, however, new methods for achieving higher characteristics are being developed. An illustration of the first case might be the weight problem, which has a currently acquired

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exclusive significance, and an example of the second is the problem of range with an attempt at control of aerodynamic currents.

It is well-known that during planning, a multitude of problems in the areas of aerodynamics, weight, strength, reliability, automation, control systems and so forth are solved. The methods of study and character of solution group these into these areas. At the same time, some of them are connected with the economoy of the airplane, for instance in the area of aerodynamics -- problems of speed, quality, takeoff and landing characteristics, and others are connected with safety (strength and controllability). In the area of strength, some are connected with economics through weight, others through resources, and many are connected with reliability.

In this work, an attempt is made to systematize and study those planning problems whose decision is directly connected with the main problem of the perfecting period -- that of increasing technical and economic effectiveness. It is these very problems which usually determine the major conception of actual plans and have the major effect on formulation of the parameters of the airplane and the character of its operation.

In the past, some designing problems (also connected with effectiveness) acquired an especially disputed character. These included the expediency of the engine fuel feeding arrangement, the area of efficient use of the twin engine design and some others.

Technological developments and the development of new construction materials has had significant influence on the increase of economic effectiveness in passenger and cargo airplanes. It is well-known that improved flight and technical characteristics are accompanied by a constant increase in mass-inertia, aerodynamic, vibration, heat and repeated loads acting on the parts, components and other elements of an airplane. This situation demands an unceasing perfection in construction. At the definite stage, the possibility of perfecting a number of traditional, widely used designs of various airplane parts is exhausted and the necessity for adopting principally new solutions arises. Certain directions in technological development, however, maintain their importance. Thus, the tendency toward decreasing the number of connections (joints) and toward using large panels and sheets, /9 whose dimensions have achieved significant size, continues to exist.

Questions of the technology and resources of an airplane and its parts, although they exercise significant influence on economic effectiveness, are not reviewed in this book, since they relate more to the area of construction than that of design.

It would be impossible not to speak of the widespread use of new alloys and composition materials since the use of these materials can lead to a revolutionary leap in airplane construction.

Problems of reliability have an essential effect on the economics of an airplane and on flight safety. They relate to the design object in that they are solved at all stages of the machines' development, beginning with the sketch plan, when the external form and general arrangement of the airplane is chosen and the principal schematics of various equipment systems are worked out.

As is well-known, rapid changes are taking place in contemporary technology. With this, it is made more complex with respect to construction, increasing the number of parts and assemblies and making the functional connections between them more complicated. A modern jet passenger airplane consists of many thousands of parts, and a mass of the most varied components, mechanisms and instruments is installed and functioning on board it. At the same time the machines are becoming ever more productive, they satisfy all new requirements, which offsets expenses. The contemporary process of the scientific and technical revolution is reflected in these phenomena, and one of the principally new forms of technology generated by this revolution is that of machine systems. From development of separate machines, they now move toward the creation of machine systems in the form of industrial complexes, power and other systems.

The subject of our inspection is the air transport system. The idea of an air bus, which is analyzed in detail in this work, was born and developed exactly as a system of movement, and the creation of an airplane-air bus is unthinkable without the development of a complex of principally new airport equipment. And the problem not only includes that of serving the ever-growing mass of passengers and handling their baggage, but also includes that of coping with the increasing intensity of traffic and with servicing giant airplanes. Indeed, saturation of the air space by airplanes on flight routes and in the area of airports is connected to the problem of air communication safety.

The complex problems of development and perfection of technical systems require a concerted approach to the determination of their efficiency. At the present time, one cannot limit oneself to analysis of the efficiency of any given machine separately. The problem must be solved in terms of the scope of the national economy by means of optimization considering the multifaceted appearance of the factor of time, convertability of resources and the effect of interaction. /10

In this work, only the problems of subsonic aviation are reviewed. The problems of supersonic passenger airplanes (SPA) [SST] is not touched on in this work. They have an independent significance and a wide area of investigation. These airplanes are further from perfection than subsonic ones, and here there are still many unsolved and perhaps unrealized problems. Besides this, for the time being no doubt arises to the fact that the preponderant proportion of future transport will be accomplished on subsonic airplanes. When supersonic ones also occupy their place (i.e. attain technical perfection and equal profitability), they will probably not become competitors of subsonic ones, but the two will complement each other.

When studying the problems uniting all the ideas on increasing efficienoy, it is difficult to avoid the questions of technical forecasting. However, for a significant period in the development of aviation it was not reliable, in the first place because the development of this area of technology is taking place significantly more rapidly than that of other areas, and in the second place (and this is important), in the process of development, not only evolutionary changes take place, but also revolutionary ones (by leaps-and-bounds), and their forecasting is made difficult by determination of the time required for conversion of the scientific achievement into a technically attainable engineering concept, and then into a commonly acceptable device. As concerns forecasts on the foreseeable future, which are usually based on extrapolation of established tendencies, they will lead to useful results. It is true that there is little probability as to the extent to which they will coincide with reality, but nonetheless, they will allow evaluation of the possible courses on development to be made. In accordance with this, forecasts on one decade of jet aviation development, namely the third one (1970-1980) are reviewed in the following.

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PROBLEMS OF DESIGNING PASSENGER AIRCRAFT

V. M. Sheynin and V. I. Kozlovskiy

PART 1. TENDENCIES IN THE DEVELOPMENT OF PASSENGER AVIATION WHICH DETERMINE INCREASED EFFICIENCY

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Chapter 1. Classification of Passenger Airplanes

1.1. On classification. It is well-known that the development of any science is based on statistics, the accumulation of experience, systematization and classification. This also relates in full measure to the science of designing airplanes. Unfortunately, a commonly acceptable classification for airplanes does not yet exist, but the existing ones are similar. The rapid development of aviation, which has considerable influence on the separate ideas and understandings, also introduces its corrections into classification. Thus, with a sharp increase in tonnage, such ideas as "light" and "heavy" airplanes become obsolescent, in that modern, and especially future short-haul ("light") airplanes are heavier than long-range "heavy" airplanes of preceding years. Classification is necessary not only for the study of the airplane development process and experience in their design, but it also makes the task of determining the required gamut of machines easier, in that having a multitude of types has its limits with respect to economic expediency.

Classification is made up according to one or more characteristics. The possibility of a second approach is usually limited to airplanes having one to two generations, but it leads to a system which eases overall comparative evaluation and creates an idea of the level of development in aviation technology.

Aircraft are divided into forms, types and classes.[1] One of the forms, airplanes includes two basic types: military and civilian. During recent years, military transport airplanes have been widely developed. Possibilities for their equal operation (without conversion) for both military and civilian purposes as well as other features allows them to be placed in an independent (third) type.

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* Numbers in the margin indicate pagination in the foreign text.

Civilian airplanes are subdivided into three groups: commercial regular line (passenger, cargo and cargo-passenger); business (administrative) and light motor (agricultural, sport and private airplanes).

Divisions of passenger airplanes having gas turbine engines according to generation are frequently found in the literature. This understanding is purely arbitrary and has no bearing on classification. It expresses development stages and technical level. The first generation relates to turboprops and turbojets, and the second relates the airplanes with two-stage jet engines and their arrangement, in the majority of cases, on the tail section of the fuselage. A feature of many airplanes of the third generation is their large-dimension fuselages and engines with a high degree of by-pass. /12

1.2. Classification of passenger airplanes is based on a study of the fleet existing in the world and tendencies in the development of aircraft construction. In keeping with this, only subsonic airplanes appearing in operation up to the 1970's are reviewed below. The classification of supersonic airplanes is not yet clear. For instance, the economic effectiveness of using airplanes having a number M = 2.2 and 3 continues to remain a controversial area. The same can be said of high-tonnage third generation airplanes, which are planned to have wide variations in range. /13

Classification of airplanes according to flight range [18, 35] is commonly accepted, since that determines the possibility of using them on lines of varying distances (see Table 1.1). The meaning of many parameters and characteristics (for instance, cruising productivity), whose value changes as a function of range is also connected with it. It is true that classification according to flight weight (light, heavy) and according to number of passengers (20-seat, 100-seat) is also encountered.[2] It is well-known, however, that each airplane, with respect to load capacity according to range, has two characteristics (Fig. 1.1), range at maximum commercial gross weight and maximum fuel economy range. The question then arises of which of these to take as the criterion. Apparently it is the first -- it determines the dimensions of the airplane, its strength characteristics and efficiency (i.e. it corresponds to the minimum cost per ton-km). With a large fuel system capacity (and low wing loading), the divergence in commercial payload weight may be significant. Its lower limit may turn out to be on the threshold of profitability or even below it. The correct selection of this characteristic

[2] They were not introduced, but for convenience in various studies, the terms "100-place module" or "200-place module" etc. have begun to be used.

TABLE 1.1. CLASSIFICATION OF PASSENGER AIRPLANES WITH GAS TURBINE ENGINES (IN OPERATION) AND THEIR BASIC PARAMETERS

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Class		Range (technical) with maximum commerical payload, kg	Takeoff weight, t	Total thrust, kg force or power (effective hp)	Number of economy class seats (maximum number)	Country	Airplanes	
							With turboprop engines	With turbojet and double flow turbojet engines
Local line (LL) airplanes	Close	500-800	Up to 6	Up to 2000	Up to 20	USSR	Be-30	--
						England	Handley-Page "Jetstream"	--
						USA	Beechcraft (Mod. 99)	--
	Far	800-1700	10-20	4000-6000	25-50	USSR	An-24	Yak-40
						England	Potez 842	Handley-Page "Herald" series 200
						France	--	
Short-Haul (SH)		1500-3500	25-55	9000-13500	60-125	USSR	An-10	Tu-124; Tu-134
						USA	Lockheed "Electra"	Douglas DC-9 Boeing 737, 727-200
						England	Vickers "Viscount", Avro-748	BAC-111
						France	--	Sud Aviacion "Caravelle"
						Holland	Fokker "Friendship f-27	Fokker f-28 "Fellowship"

[Continued on following page]

Table 1.1. continued

Class	Range (technical) with maximum commerical payload, km	Takeoff weight, t	Total thrust, kg force or power (effective hp)	Number of economy class seats (maximum number)	Country	Airplanes	
						With turboprop engines	With turbojet and double flow turbojet engines
					Japan	JS-11	--
Medium-Haul (MH)	3500-500	50-80	13000-22000	60-190	USSR USA England France	Il-18 -- Vickers "Vanguard" --	Tu-104; Tu-154 Boeing 727-100 DeHavilland "Comet 4," "Trident" Sud Aviacion "Super Caravelle"
Long-Haul (LH)	5000-7000	85-125	21000-30000	130-180	USA	--	Boeing 707-120; Boeing 720; Douglas DC-8-20; Convair 880
Inter-continental (IC)	7000-10000	140-165	33000-46000	170-200	USSR USA England	Tu-114 -- Bristol "Britannia"	Il-62 Boeing 707-320; Douglas DC-8-50, DC-8-60; Convair 990 Vickers VC-10

is also important for parametric analysis. One should also be warned against the erroneous impression which is sometimes encountered that the maximum values for range, payload capacity and speed can be achieved simultaneously.

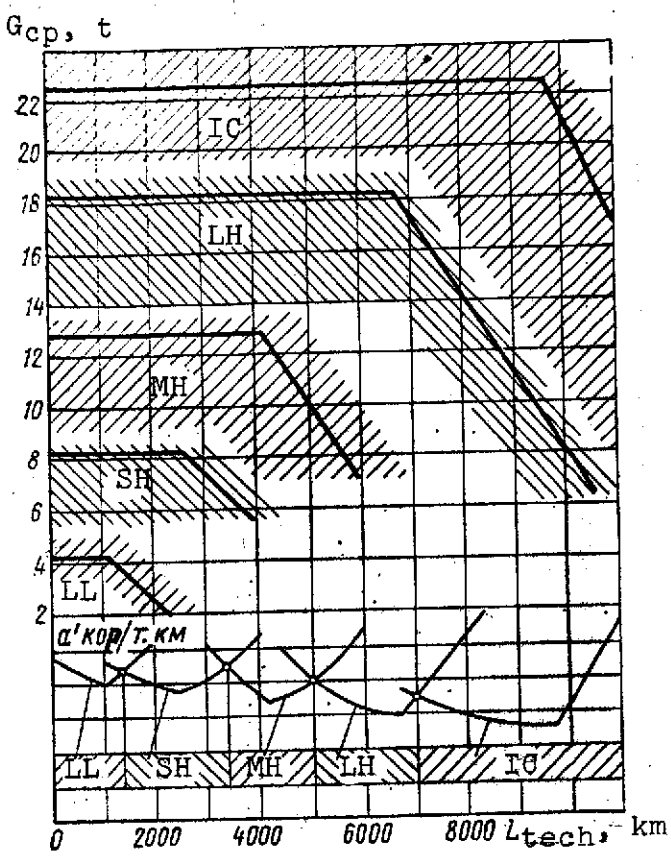

Fig. 1.1. Change in commercial payload (G_{cp}) and transportation costs (a') depending on the flight distance of airplanes (first two generations). Designations according to Table 1.1.

Table 1.1 presents the classification of turbofan and turbojet passenger airplanes which went into operation up to 1970, which includes five classes[3], placed in the sequence of range increase, total thrust, airplane gross weight and number of passenger seats. The values for these parameters are located within relatively narrow limits and increase regularly from class to class[4]. The latter of these parameters, true, is not particularly regular in its change, and in short-haul and medium-haul airplanes, its value lies in a wide range, which is explained by the presence of a large number of modifications. The lower limit of the values shown corresponds to the original variation, and the upper one corresponds to the latest modifications. It should be noted that some of the airplanes listed in the table have parameters which do not coincide with the limits indicated, i.e. they are exceptions in some form. This is explained by various reasons and, for the first place, by limiting the possibilities /14

[3] Some classifications are limited to four classes [35].

[4] Other parameters of an airplane, for instance, flight speed, wing loading and power change in approximately the same sequence.

of the airplane, with rigid requirements for takeoff and landing characteristics, which leads to the underloading of airplanes in operation or resizing those planned.

It is natural that the values of characteristics shown in Fig. 1.1 and in Table 1.1 are changing and that airplanes of future generation will not be entered within the limits of the values presented. However, the structural diagram of such a classification will evidently be maintained. It would be appropriate to note here that the length of the cruise in determining the class of the airplane will also change with the development of aviation. Thus, during the period of distant aviation, short-haul airplanes included those with a nominal flight range of up to 2000 km, the range increased to 2800 km for turboprop airplanes and up to 3500 km for turbojets. It is expected that it will increase up to 4000-4500 km for airplanes of the future generation. Therefore, it is expedient to make up similar tables, classifying airplanes according to what has been said.

1.3. On the gamut of the airplane fleet. It is well-known that the selection of the number of required types (or the gamut) in airplanes is a complex problem. Its solution is complicated by the presence of two independent questions -- on a number of airplane classes required and on the number of types within each class. The term "type" is understood here to mean different designs for airplanes of approximately the same size). The fact of the matter is that multiplicity increases not only due to the expedience of parallel planning on approximately equal sized airplanes (which will be dealt with later), but also due to the fact that there are in operation airplanes having several (a minimum of two) generations, increasing the quantity of design types. However, only airplanes on a single technical level can be used for examples of study in this case. This question, just as the majority of others, conceals a definite contradiction within itself. On one side, the variation in types makes operation more complex, increasing the scope of ground equipment, spare parts and so forth. On the other side, the construction of two equal sized airplanes for the same purpose creates rivalry (or competition), which leads to the creation of more perfect airplanes both during planning and during their modification. It is impossible not to also consider that only through massive operation will be achievements and deficiencies in the airplanes become fully clear and a sort of natural selection will occur. In the process of this /17
selection, the better ones will endure a series numbering many hundreds (Il-18, Boeing 707 and others). The run of unsuccessful or "late" ones will number in tens ("Vanguard" and others). Worldwide practice shows the advisability of simultaneously developing equal sized airplanes (with approximately the same payloads and passenger seating) but different in design, for instance, the Tu-104, Il-18 and An-10 or the Boeing 707 and DC-8 or the DC-10 and Lockheed L-1011 (USA). Fig. 1.1 graphically presents the basic characteristic -- payload as a function of range -- with

values which are typical for aiplanes of the five classes.[5] By comparing these characteristics it can be seen that airplanes of different classes can be used on routes of the same length. The area of economic expediency for their use can, in the first approximation, be found by means of determining the total cost of a ton-kilometer or a passenger-kilometer (a'). The results of similar computations are presented there as an example.

The cost of operation is determined according to a method by E. A. Ovrutskiy [3] with the roughly accepted initial data (according to resources and other factors) which are common for all airplanes. The straight lines, passing through the points intersecting the curves, are limited on the scale of zone range (SH, MH, LH and IC, which correspond to the optimum route lengths. There exists, therefore, two critical value for route length, above and below which each given airplane falls behind airplanes of other classes in economic effectiveness. In accordance with this, for determining flight range (with the reviewed level of passenger movement) the optimum type of aircraft, as well as the required number or required gamut of airplanes can be found. The number of airplanes in each of the classes is determined by means of studying the possible growth in the volume of passenger transport and the required frequency of trips on lines of various length. Also included in this is the possible development of industrial or other enterprises in populated areas which are connected by air lines as well as the increase in passenger flow due to a possible decrease in fares. The distribution of lines between airplanes on the basis of transportation costs (see Fig. 1.1) is the general position. Operating conditions naturally have their influence. Thus, for instance, a line with an increased density of passenger flow, on which, according to this approach, the use of airplanes with a large number of passenger seats might be advisable, is an exception.

The graph shows curves which are characteristic for jet airplanes of the first two generations. The gamut of airplanes of /18
the third generation has not yet finally been determined. It is clear only that payload capacity and number of passenger seats in each of the classes and, consequently, also the gross weight of the airplanes will increase sharply.

Chapter 2. Tendencies in the Development of Passenger Airplanes with Gas Turbine Engines

2.1. Courses of development. Various courses toward the study of historical processes exist. Some of these are connected with the history of factors and objects. Other are connected with

[5] Characteristics for almost all turbojet airplanes coming into operation up to 1970 are included in the striped areas.

the studies of development tendencies and analysis of the dynamics of change in the parameters and characteristics of these objects. It is clear that not every object created or even those going into operation represents a stage and that not all tendencies deserve attention. Some of them died off, others survived and were developed, and others became leaders and universal. Their analysis, just as the study of factors, objects and chronicals of development, is usually based on statistical materials, accepted criteria and classification. It should be noted that only planning which is based on the study of development tendencies and technical and economic research is progressive and allows for the creation of promising airplanes, because development tendencies reflect objective changes in air transportation. Those airplanes might be considered promising which, being effective in their initial variation, possess a potential possibility for modification development. Two lines can be differentiated in the development of modern civilian aviation: the creation of more perfect models and the development of modifications. The second of these is comparatively new and has a great and independent significance. It is reviewed in Chapter 4. Concerning development along the lines of creating new models, piston airplanes were developed with a progressive increase in overall size, which was determined by the airplane's gross weight. In a development of jet aviation, creation of heavy-tonnage airplanes was characteristic from the beginning. This is explained by the fact that large airplanes allow for the use of jet engines to attain high flight speeds to a greater degree. Besides this, high weight and economic characteristics are more difficult to achieve in airplanes of the lighter tonnage. Up to a certain time, the development of airplanes in strict sequential increase or decrease in tonnage was a regularity, whose technical sense was in part included in the progressive design solutions in creation of engines and airplanes.

We recall that the massive operation of gas turbine passenger airplanes began with the turboprops[6] weighing 50 to 80 tons: the An-10, Il-18, "Britannia," "Vanguard," and "Electra." The only exception was the "Viscount" (26-30 t). After that, airplanes /19
weighting 12-25 t were planned: "Friendship," Avro-748, "Herald," An-24, "Potez," and others. The Tu-114 was built with a weight of over 150 t. The regular operation of airplanes with turbojet engines began in the USSR in 1956 (with the Tu-104), and in the west in 1958, when the turboprop fleet was already considerable (in the ICAO countries, for instance, there were 418 airplanes with turboprop engines and a total of only 12 with turbojet engines). The first turbojet engines were installed primarily in long-haul and intercontinental airplanes. The development of airplanes with turbojet engines for short and medium hauls which were capable of competing with turboprops became possible only with the appearance of two-stage engines.

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[6] The Tu-104 was the first airplane to appear in operation in the USSR.

The first generation of turbojet airplanes included the Tu-104 and "Comet" (weighing 71-76 t), and then the Convair 880 (87.8 t) and Convair 900 (114.7 t), and the Boeing 707-120 and DC-8-10 (115-125 t, respectively). The "Caravelle" (42 t) was an exception. Airplanes appearing in the second generation included: medium-haul -- the "Trident," Boeing 727 and Tu-154 (60-90 t); short-haul -- the Tu-124, BAC 1-11, DC-9, Boeing 737 and the Tu-134 (weighing 35-52 t) and the intercontinental Il-62, Super VC 10 (152-160 t); and also the new modifications, Boeing 707-320 (148 t) and DC-8-60 (158.7 t). And finally, airplanes with the very least dimensions were created -- the turbojet Yak-40 and the turboprop Be-30 for local lines, weighing 13.7 and 5.7 t and abroad, the Fokker F-28 "Fellowship" (25 t).

It should be noted that the development of air transportation elicited a sharp demand for short-haul and local line airplanes, which handled a large volume of transportation. Their creation, however, turned out to be a complex business. Many projects were announced abroad "to replace the DC-3," and domestically "to replace the Il-14," but creation of really viable successors failed for a long time. This was first of all because attainment of the weight performance necessary to achieve high economy is immeasurably more difficult in airplanes of low tonnage than in those of medium or heavy tonnage. This is explained by the fact that wing loading must be kept moderate due to airport requirements, and the specific weight of the equipment is to high. Besides this, it is difficult to combine two such factors as low operational expenses per ton-kilometer and short flight distance. The reasons for the high cost of short flights are well-known: frequent landings, which essentially increase the idle time of the airplane, decreases the flight and hinders the effective use of the crew's working time. A decrease in the number of flying passenger kilometers per year decreases profitability and airport expenses have to be related to the minimum annual income. In the long flights, the profitability increases by increasing the number of passenger seats, but this, as a rule, does not pay for itself on lines of short length, where the frequency of flights must be high.

The complexity of creating a jet airplane for local lines, capable of operating off limited size dirt airports on one side, and the necessity to replace piston equipment on the other led to a situation such that in the mid-1960's, a competition was organized in the USA for the best airplane of this class. The conditions of the competition were, in part: passenger seating for 14-30 persons, flight range of 1100 km, and introduction into operation by the beginning of the 1970's. Not one of the nine projects submitted to the competition was accepted. The problem of creating such an airplane was solved in Russia. The Yak-40 proved to be a completely original, highly successful and promising airplane. In flight speed (550-600 km/h), it significantly surpassed its piston engine predecessors.

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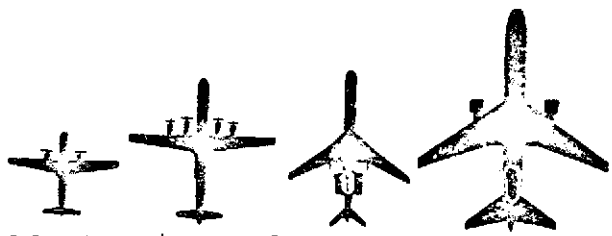
Modern passenger aviation developed in a sequence which was approximately connected with the peculiarities of the development of gas turbine engines. A more rigid conformity can be noted if the growth in dimensions and tonnage of airplanes in each of the classes can be reviewed [63, 91]. The reason for growth in this case was the appearance of new types of engines, and the result was a constant and surging increase in passenger seating capacity. With this, the full growth in the dimensions of airplanes of each class over the past 30 years is highly significant (Fig. 1.2). Passenger aviation in, for instance, the USA has developed similarly. Equal in size to those shown in Fig. 1.2 in the USA were the Douglas DC-3 with piston engines, the Lockheed "Electra" with turboprop engines, the Boeing 727-200 with medium stage double flow turbojet engines and the Lockheed L-1011 with high stage double flow turbojet engines. The leap over this 30-year period of development is illustrated by the example of airplanes built by Douglas, the oldest aviation firm (Fig. 1.3).



Il-12, Il-14 Il-18 Tu-154 Aerobus

Fig. 1.2. Growth in dimensions of airplanes designed for lines with maximum passenger flow of the type Moscow-Adler.

It is clear, naturally that the course of the development of passenger aviation is characterized by many factors. Here, we are only briefly reviewing the evolution of the airplane's size, which is also a determining factor in the dynamics of change of its parameters and characteristics, and in the productivity and the economy of air transport means. Airplane size as a design problem is analyzed in Chapter 13, inasmuch as it is inseparable from the problem of weight. /21

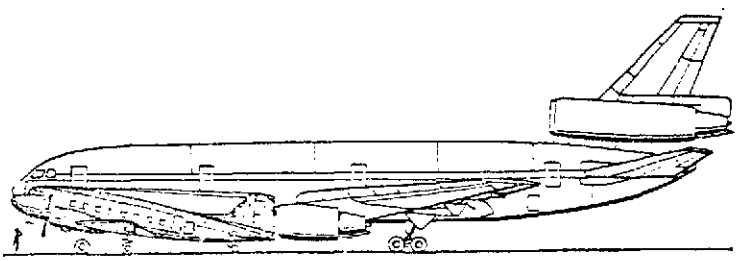


Fig. 1.3. From the DC-3 (1935) to the DC-10 (1970).

In conclusion, it is appropriate to talk about the "time factor." Is the fact that some airplanes turned out to be first always significant? In the "becoming" period of aviation or at the moment when the next revolutionary leap matures, when possibility for realization of principally new ideas is proven or new paths are cleared with a previously unattainable flight range, the time factor,

naturally, has a great deal of significance. In our time, the role of this factor diminishes noticeably. The fact of the matter is that aviation technology in various countries is basically developing equally, or to be more accurate, with small oscillations in the level of technical perfection. Any time advantage cannot last very long and evens out very rapidly. Under these conditions, the effect of technical and economic perfection of the passenger airplane is more essential than the factor of time. The "Comet" and Boeing 707 airplanes can serve as an example. The production of the first has long since stopped, and that of the second continues. One must not forget, however, that the sad experience of the catastrophes of the "Comet," during the creation of which "virgin soil was plowed" and the designers encountered the phenomenon of fatigue strength with the effect of repeated stress, was realized in the second airplane. Foreign short-haul jet airplanes serve as another example. Two recent ones proved to be more effective than their two predecessors, and their production is twice as large. It is true that the propositions of "premature" introduction into operation and introduction with a "delay" exist, but this is another question. It is connected to actual conditions and is determined by economics.

There are several similar cases in the history of aviation. /22
If one can agree with this position, which is also possibly disputed, than it is easy to reach the conclusion that competition with respect to periods of creation is so expensive that the efficiency of the equipment is doubtful. The end result is more significant. It is appropriate to recall a similar assertion of a well-known scientist, who said that it is impossible to convert achievements in space into an object of competition, for otherwise science can be lost. One should not look for the opposite assertion that the "first" is successful in that which has been said. An attempt has been made here to illustrate the expediency of the tendency. It is clear, naturally, that creation of the "first" is more complex than that of later ones, and this is the entire question for which we are striving. If under certain conditions the time factor also acquires significance, then the optimum compromise between effectiveness and the time of introduction into operation may be found on the basis of broad analysis. The meaning of high characteristics, just as that of low cost is evident. The value of an earlier period for introduction into operation requires exacting review. An exception to this might be a case in which an obvious deficiency in the given type of equipment is sensed.

A situation which was in some measure similar occurred in the previous planning of airplanes for, if it can be stated thus, one parameter, i.e. a striving to achieve a specific high value for one of them (for instance, speed) to the detriment of the others. It is well-known that the latter cannot be avoided, and effective airplanes can be created only with the harmonious combination of all parameter, whose optimization is conducted on the basis of economic criteria.

2.2. Directions in planning. The rate of development in transport aviation and the level of technical perfection in airplanes depend on many factors. Directions in planning, for instance, also have quite a bit of influence. In the "becoming" period of Soviet gas turbine aviation, several principally different courses for planning air transport means were charted. Some of them were distinguished by their widespread use of the principle of succession. In other words, the creation of passenger airplanes was based on previous models with maximum use not only of construction elements but also of airplane parts, power units, equipment or aerodynamic and overall arrangement. The second direction was distinguished by the creation of airplanes for multiple purposes. The third was distinguished by development of original passenger airplanes for a single purpose and refusal to use existing engines and parts of airplanes in operation.

Each of these directions in planning had its achievements and its deficiencies, and they all played definite roles in the development of civil aviation. Airplanes from the first direction were created with power units and equipment systems which were already well developed, enabling a shortening of time periods and /23 a decrease in resource expenditures on creation of experimental models and on introducing them into operation. This added to the economic effect, inasmuch as it is well known from worldwide practice that the unavoidable period for finishing off a system and mastering new technology does not allow the airplanes to be used during the first years to the same degree as they can be used during succeeding ones. Consequently, this direction led to a gain in time, to a decrease in initial expenses, and, by this, to an increase in economy during the initial period of operation.

Airplanes of the second direction, distinguished by their multiplicity of purpose, were easily converted for various types of cargoes. The fuselage selected for these conditions led, naturally, to definite (for the passenger variation) economic and weight losses. Further development of the basic idea in this direction can be seen in the appearance of cargo-passenger airplanes whose dimensions were selected based on the conditions of the passenger variation.

Airplanes from the third direction, by comparison with the first, require both a great deal of time and a great deal of resources for development of plans and for creation and testing of experimental models. At the same time, this direction allows the useof all the newest achievements in the area of aerodynamics, engine construction, technology, metallurgy and other sciences, enhancing the creation of promising airplanes and rapid, in the final account, development of aviation technology. Operational practice has shown that the economic advantage remains behind airplanes from the third direction. As the result of this, it has become universal.

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The ways of planning can also be differentiated by their approach to the selection of engines. Planning airplanes on the basis of existing engines allows time to be gained and rival organizations to be outraced. Planning on the basis of prospective engines somewhat slows down the process of introducing the airplanes, but allows the creation of more highly perfected equipment. The position on advisability of planning airplanes and engines in a parallel manner, however, is not without dispute for a number of reasons. Firstly, the creation of a new engine occupies more time than the creation of an airplane and, secondly, a great deal of resources are required. If existing engines have the potential for development[7], high resource and reliability, they may turn out to be preferable. An example of this might be the English Rolls Royce "Derwent" engine, which is not distinguished by its high economy but has a long life and reliability, and was therefore widely used during the period of turboprop aviation.

The question on economic expediency of the degree of succession, /24 touched on above, is interesting and controversial. It is understandable that the creation of any qualitatively new models is impossible without the use of components and units or parts of systems from preexisting products, as well as design solutions found earlier. Determination of the area for using the principles of succession is complex. It does not have to contradict a bold approach to the use of anything new. At the same time, all that which has been tested in operation and put into series production is very inticing. This question also has its optimum solution. If the new will lead to a definite qualitative leap, it is preferable and if it does not mean development, then the choice of innovation for the sake of innovation will not find any allies. The eternal problem of selection, arising in many questions of design, is also reflected in this case. Planning practice in leading offices is a distinctive striving toward the expedient combination of innovation in cardinal questions and succession in design decisions. The degree of succession is determined by means of finding the total result with consideration for the influence of negative effect, which is sometimes called the "calculated effect of lost possibilities.". The wise and well-founded use of the principle of succession increases economy. Therefore, the advantages provided by commonalities are also not given up and maintenance of the successive connections which are characteristic for the given series of airplanes is strived for. The question of succession adjoins the more general problem of unification. It would be hard to overestimate its value in our time. Everything that is perfected and progressive is, without a doubt, unified. The degree of unification is often expressed in qualitative indices

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[7] Engines, just like airplanes, possess a potential for development, i.e. the possibility for increasing thrust (more detailed in Chapter 4).

(in %), which is hardly right. The cost of one unit, for instance, a pump is incomparable with the cost of an engine. The cost expression of the degree of unification (in % of the total) is a more objective index.

The development of passenger aviation has its own directions, which are similar to schools in the sciences. They are connected with the names of Antonov, Il'yushin, Tubolev and Yakolev. Their collectives have their own style, their own traditions. Their technical politics, providing development in various directions, promote the rapid growth of domestic aviation.

The youngest of those listed is the O. K. Antonov Separate Design Office, but a whole series of original designs have already been created there, including the "Pchelka," the smallest airplane and the "Antey," the largest in Soviet aviation.

The unique An-10, a first generation airplane, foretold not only the development of a class of cargo-passenger variations of second generation airplanes, which have already been recalled, but also the development of wide fuselages in passenger airplanes of the third generation. The major direction of the collective was determined by its leader: "the characteristic peculiarity in the /25
technology of today is its maximum optimization, which is to say the achievement of maximum results with minimum expenditures." This collective has been attributed with its own characteristic bold innovations, not only in planning and design, but also in technological solutions.

S. V. Il'yushin defined his direction thusly: "We always strive for the achievement of perfection in airplanes which is characterized by the best accomplishment of their purpose, which is to say to the achievement of the highest combat readiness in military airplanes and the maximum productivity in civilian ones. Extended and mass production and operation can be given to only those airplanes which more fully accomplish their missions" [23]. The record production runs, high longevity and technical perfection of his machines are spoken of in many works. Monuments are erected to the legendary Il-2, which the enemy named none other than the "Black Death" as well as to the airplanes of A. I. Mikoyan and A. S. Yakovlev. A detailed analysis of the Il's in comparison with foreign airplanes is presented in works [22, 23], and the revealing of this collective's secret of creative success, which led to exclusive mass production scale and longevity in all airplanes released for series production, awaits its investigator.

The oldest, Tupolev collective, was formed during the period of the "becoming" of Soviet aviation. Many various models of aviation technology were created by it. During recent years, it created the first supersonic Tu-144 and the medium-haul Tu-154 with two-stage jet engines. Defining his direction, A. N. Tupolev

said: "The major thought in our work consists not so much of creation of certain types of airplanes as the solution of many problems in airplane constructions" [55]. The principal diagrams developed here were new for domestic and worldwide aviation. Many bold plans of its leader were accomplished by the collective from the moment when the "decisively stood on the path to construction of airplanes out of light alloys."

A new standard bearer for light aviation appeared in air transport at the end of the 1960's in the form of the Yak-40 design by A. S. Yakovlev, with his name is connected one of the Russian schools in the development of fighter aviation. Many various types of aviation technology were created in this Design Bureau, and its light-engine aviation also achieved widespread notoriety. The Yak-40 passenger airplane, distinguished by the originality in its overall layout and unique design, continues the development of local line aviation (the AIR-6 and Yak-12 airplanes of this class were built earlier in the initial Design Bureau).

2.3. The dynamics of characteristics in the process of airplane development allows the noting of definite regularities, whose meanings are not necessary for well-founded forecasting.

The planning of a passenger airplane with a high subsonic flight speed and high productivity is subjected to a multitude of interrelated requirements, among which the determining ones are: commercial payload (or number of passengers), flight distance, cruising speed necessary for achieving maximum economy in the airplane (within the scales of the fleet), and takeoff and landing characteristics. All of these influence the dimensions of the airplane and its economy. Requirements in this group have their own qualitative indices. Another group of requirements which allow primarily qualitative evaluation and only tangentially affect economy includes: reliability of construction and equipment, flight safety, necessary comfort for passengers and maximum convenience for the work of the crew, provisions for simplifying servicing of the aircraft on the ground and its increased adaptability for repair. /26

The basic prerequisite for the development of passenger airplanes which determines an increase in their economy is the constant increase in the requirements of the first group, and the means for their fulfillment are: an increase in dimensions (tonnage) of the airplane, increased specific wing loading, aerodynamic and weight perfection of the airplane and gas dynamic perfection of the engines. In other words, the fulfillment of these requirements is determined by solution of the major problems of planning: the selection of optimum aerodynamic layout, appropriate parameters and power supply, i.e. the achievement of the best correspondence between the glider and the power installation and also solution of the weight problem.

Satisfaction of these requirements does not, however, exhaust the task of the designer. There exists the necessity to analyze results, and often also to formulate the requirements themselves. Knowledge then comes into play on tendencies of development in air transport and predictions on growth of the scale of transportation, and on the basis of all that an exacting investigation into the required dimensions of the airplane, since passenger seating capacity, its determining dimension, is its most complex problem. Its solution must correspond not to the situation existing in aviation at the given moment, but must be determined with consideration for the development of air communication and must consider the demand for the coming 8 to 10 years. The complexity of this problem, like others connected with predictions on development rates, consists of an economically founded forecast. Methods for determining the increase in demand have been worked out, allowing the use of mathematical machines and the degrees of confidence of the results used for evaluation. With this, the possibilities for developing industrial or resort areas connected by air lines is being studied. Operational data indicate that the practice of analysis itself and the methods used are effective, and that a correspondence between supply and demand exists. The value for the coefficient of passenger loading, which was relatively /27 stable during the course of the last period, testifies to the fact that an increase in the number of seats actually corresponds to an increase in passenger flow.

During the age of piston aviation, passenger seating capacity increased simultaneously with an increase in flight distance, and during the period of gas turbines, its increase is observed in airplanes of all clases (Fig. 1.4). The courses of this growth are, however, various. It is reviewed in more detail in section 1.4. The commerical payload weight increased similarly to an increase in passenger seating capacity and tonnage, i.e. smoothly according to flight distance and in leaps according to stages of development, with the appearance of new types of engines.

Another tendency in the development of aviation, also universal and constant, is the constant increase in flight speed (Fig. 1.5 and 1.6), which occurs smoothly when one engine type is maintained (with an increase in aerodynamic perfection) and in leaps with a transfer from one type of engine to another. Speed also increases with an increase in flight distance, since the means for achieving high speeds in short-haul airplanes are not justified economically. The quantitative leaps in airplanes of the various classes are therefore varied: in short-haul airplanes over a 40-year period (1935-1975), flight speed and load capacity increased by 3 and by 10 times and in long-haul airplanes, they increased by 8 times (considering the SST) and by 21 times (Boeing 747) respectively. During this time, with each new generation of jet airplanes, flight speed increased by approximately an amount corresponding to $M = 0.05$. The jump in speed occurs, as is already known with the move to supersonic passenger

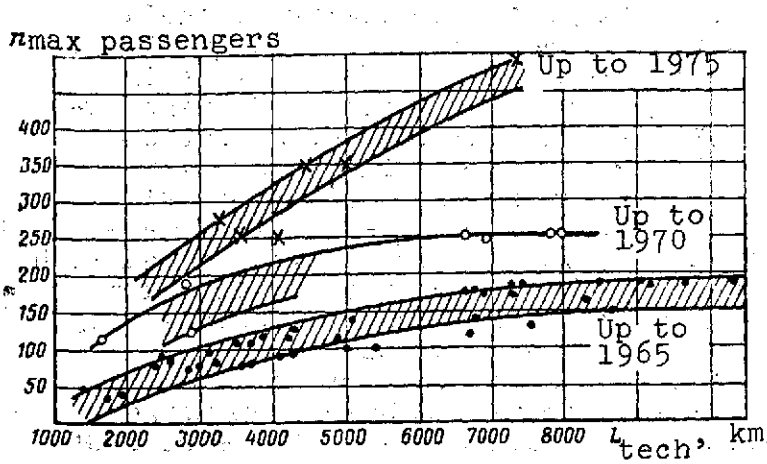

Fig. 1.4. Changes in maximum passenger seating capacity depending on flight distance: o -- Initial variations of airplanes; o -- Their modifications; x -- Aerobuses

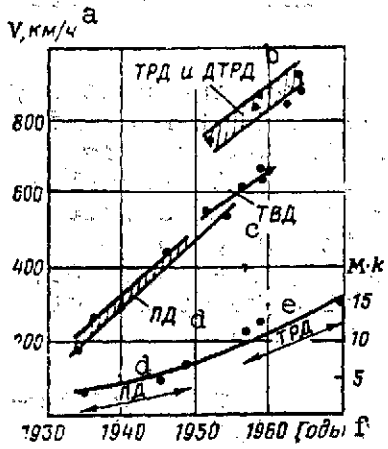

Fig. 1.5. Increase in speed V and aerodynamic effectiveness M·k in the process of development of domestic and foreign airplanes.
Key: a. km/h; b. Turbojet and double flow turbojet engines; c. Turboprop engines; d. Piston engines; e. Turbojet engines; f. Years

aviation by up to M = 2.2 in the Tu-144 and "Concorde" airplanes and up to M = 3 in the Boeing 2707. The creation of an airplane with a speed corresponding to the number of M = 1.2-1.4 is not excluded, however, although there is great aerodynamic resistance in this area. It is thought that this speed, providing a significant decrease in flight time, would not require solution of some complex technical problems which are encountered during development of higher speed airplanes. In particular, it is thought that with a number M less than 1.4, sound shocks will not be a problem, but economic gains by comparison with, for instance, M = 0.98 are not expected ("Interavia," 12, 1971). /28

2.4. Growth in transport and economic effectiveness. The first of these is characterized by productivity and is that part of economic effectiveness on which the aviation designer has immediate influence. The second includes many conditions of production (product cost) and operation. The aviation designer influences it only tangentially -- through technological effectiveness of the design, and he influences operating conditions through comfort, reliability, and ease of performing repair. Increased technological effectiveness and comfort will lead to an increase in passenger loading, and an increase in ease of repair and reliability will lead to a decrease in service time. In accordance with this, analyses of transport effectiveness are used in design practice on the same level as economic ones. At the basis of these analyses lie hourly ($G_{cp}V$) or range ($G_{cp}L$) effectiveness. The /29

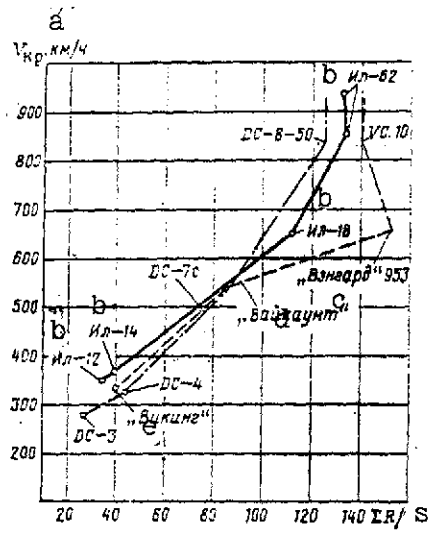

Fig. 1.6. Speed increase with examples of airplanes designed by S. V. Il'yushin (solid line), the Vickers firm (dashed line) and Douglas (dashed and dotted line).

Key: a. V_{cr}, km/h; b. Il; c. "Vanguard"; d. "Viscount;" e. "Viking"

criteria for transport effectiveness are various. One of them [62] is based on a comparison of the available productivity with losses in the airplane's mass (G_{ef}) and fuel energy (G_f). It is understandable that transport effectiveness does not determine economy of the airplane, inasmuch as it considers only part of the factors which determine the cost of operation. It determines the technical perfection of the airplane under stable, even conditions.

Of the two types of productivity mentioned, the latter is a more objective criterion, and the first, which does not consider flight distance, may lead to erroneous results, since during short flights on any airplane, a speed can be achieved which is significantly greater than that used in calculating the distance corresponding to a flight with the maximum commerical payload. Besides this, the dimensions of the airplane and its stability are also determined by a characteristic corresponding to a flight with the maximum commerical payload for the calculated (upper possible limit) distance. The criterion of daily productivity encompasses a greater number of factors. It considers the daily flight time, and consequently, distance, speed, and finally, load capacity of the airplane.

Load capacity is commonly understood to mean the capacity to transport a load with consideration for strength (or takeoff weight) and the possible use of the volume of the fuselage (with installation of various numbers of passenger seats, during flights with an unfilled number of passengers over a distance greater than that calculated). The possibility for using the airplane in a cargo-passenger variation and other peculiarities for each given airplane are also considered.

With the appearance of a sufficient quantity of cargoes on air transportation, the tendency appeared toward increasing the baggage and cargo sections so that the so-called "commerical payload," limited by volume" (more accurately, load space with a lower than maximum number of seats) would approach the "commercial payload limited by strength" (for more detail, see Chapter 8).

The characteristic of load capacity according to range, consequently, is not determined singly by the maximum commerical payload, but is set up graphically as a function of range. If we take the curves abc (Fig. 1.7), commerical payload limited by strength as the base, then curve ehc will be the characteristic of commerical payload limited by volume. Movement of the curve bc in the direction of de may occur either as the result of improved aerodynamic quality or a decrease in specific fuel consumption, and its movement in the direction fg would occur due to an increase in flight weight (by comparison with de). The latter curve is characteristic of more effective airplanes. The inclined parts of the curves are defined by the equation $G_{zp} + G_f = \text{const}$, or $G_o = \text{const}$. The angle of their inclination depends on the range parameter $M \cdot k/c_R$. /30

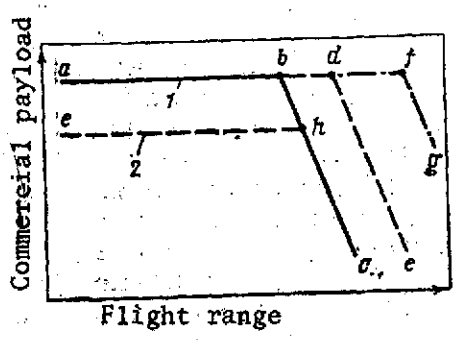

Fig. 1.7. Different appearances of characteristic for changing commerical payload according to range: 1 - commercial payload limited by strength; 2 - commercial payload limited by volume.

During the period of piston aviation, a relatively rapid increase in productivity was observed due to the appearance of airplanes of increased dimensions. Thus, during the 1951-1959 period, the average increase comprised 7.5% per year. With the introduction into operation of large jet airplanes in 1960, productivity began to increase sharply and during the course of the first four years, it increased by approximately 18.5% per year, after which the rate decreased and stabilized at a growth of 9.5% per year, since the conversion to operation of jet airplanes began to be accomplished more slowly during the later years. It would be easy to assert that in the 1970's the rate of growth will increase due to the introduction into operation of large-dimensioned airplanes (aerobuses) and SSTs. The leap will not, however, be as great as in previous periods. The basic criteria for economic effectiveness are direct operating expenses (DOE) and full ones (with consideration for tangential ones). They are expressed in absolute quantities (the cost of an airplane-hour), or in relative ones (cost per ton kilometer). The latter ones relate either to available productivity (in ton kilometers or in passenger kilometers), or to actual ones with consideration for the coefficient of fill. We remember that the DOE includes expenses connected with depreciation of the airplane and engines (initial cost), the cost of repair and technical servicing (including spare parts) and flight expenses (crew salary and fuel costs). Tangential costs include airport expenses. Other indices of economy are profitability and, in particular, the threshold of profitability, which

determines the break even level of loading according to the number of passengers. It is sometimes expressed through the threshold coefficient of passenger loading, which represents the relationship of the number of passengers at threshold profitability to the available passenger seating capacity. It is also called the balancing coefficient of fill for the airplane, implying with this the percent of fill at which profitable operation of the airplane begins. The value for this coefficient has a tendency toward constant and rather even decrease according to time. Thus, over a 10-year period (1957-1967) it decreased by almost 25%, which is characteristic for foreign aviation[8]. /31

It is already known that the basic factors influencing the economic effectiveness of a passenger airplane with a given flight distance are: weight of the empty fitted airplane (G_{ef}), aerodynamic quality (q), specific fuel consumption, c_r and flight cruising speed (V_c). It is also known that the degree of their influence is far from uniform. With this, different authors evaluate the effect of these factors differently even for airplanes having the same flight range. For instance, judging from one economic analysis[9], it follows that a change in the SOE with an even relative change in the listed amounts (by 5%) is in the relationship: $\Delta a(G_{ef}):\Delta a(q):\Delta a(c_r):\Delta a(V) = 8:2:2:0.6$. These possibly disputable but curious results were obtained during the review of a turbojet airplane with a flight range on the order of 5000 km. By changing the range, naturally, a noticeable redistribution of the degree of the effects of these parameters occurs. One way or the other, it is doubtless that the effect of the first characteristic is very great and that decreasing the weight of the machine, its equipment and engines is an effective means for increasing air transport economy.

Operational costs per airplane hour, which increased steadily during the period of piston aviation (the 1950's), began to increase rapidly with the introduction into operation of jet airplanes (the 1960's). This was expressed both as an increase in the dimensions of the airplane and as a significant increase in the cost per kilogram of the airplane (Fig. 1.8)[10]. The latter may be explained by the extreme saturation of airplanes with complex electronic equipment and the continuing increase in the cost of building the glider, which in its turn is explained by an increase in the proportional cost of labor in the total cost of the airplane. It is already known that the cost of material in any type of construction is many times less than the cost of labor. The relationship

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[8] "Aeroplane," 11.IX-1968, p. 4.

[9] "Aeroplane," 1.XI-1962, p. 9

[10] Fig. 1.8 a shows the degree of increase. With this, the cost of airplanes in 1953 is taken as the base unit.

of these values is located within limits of from 1 : 2 to 1 : 5. However, the growth rate of operating expenses was lower than the growth rate for productivity of airplanes, and therefore the operating expenses per available ton km or per actual ton km began to decrease. This tendency will apparently also continue into the 1970's with the appearance of new generation of subsonic airplanes. The question on the influence of the introduction of the SST on the cost of transportation is still insufficiently studied. It is thought that during the first stage, no decrease will occur. In this case, a decrease in the cost of a ton km is connected with an /33
increase in productivity (Fig. 1.9). When it is successfully increased without changing the dimensions, and consequently the initial cost of the airplane (for instance, by increasing component arrangement density), the dependency between these factors is linear. When the dimensions of the airplane and the type of power unit are changed, the dependency is more complex.

A review of the data illustrating the dynamics of domestic and foreign airplane characteristics will lead to the following conclusion: the rate of development of those and other airplanes is approximately identical. Their technical perfection (determined primarily by flight speed, productivity and weight effectiveness) is for all practical purposes on a single level. Similar conclusions were agreed on with announcements in the foreign press during the time when the Il-62 appeared on international lines. Thus, the American technical journal "Aviation Week" (from 22 July 1968) wrote: "The opening of direct Moscow-New York air transportation on Il-62 airplanes demonstrated the capability of Aeroflot to compete with the international aviation companies on long-haul routes...no doubt remains to the fact that Soviet aviation can move abreast of the leading Western aviation companies." The chief engineer of the American firm Lockheed, Robert Ormsby, said in an interview for "Astronautics and Aeronautics" magazine (October 1969), "The general impression which I received when inspecting the Il-62 was that it is a well done and artfully done practical design. It is one of the airplanes which is well planned for operations. Its systems create the impression that their development was conducted with the goal of assuring simplicity in manufacture and simplicity in technical servicing...the Russians take pride in their airplane, and it deserves it. The Il-62 airplane /34
without a doubt gives rise to essential satisfaction..."

2.5. The appearance and development of civilian cargo-passenger and cargo airplanes. With the introduction into operation of large gas turbine airplanes, two tendencies toward using the volume of the fuselage during flights with an unfilled number of passengers were determined. The first of these led to an increase in the volume of the baggage and cargo compartments by means of increasing the dimensions of the fuselage along its vertical axis, and the second led to the appearance of rapidly convertable airplanes for transporting cargoes on pallets in one of the passenger cabins. The reasons for the appearance of these tendencies were

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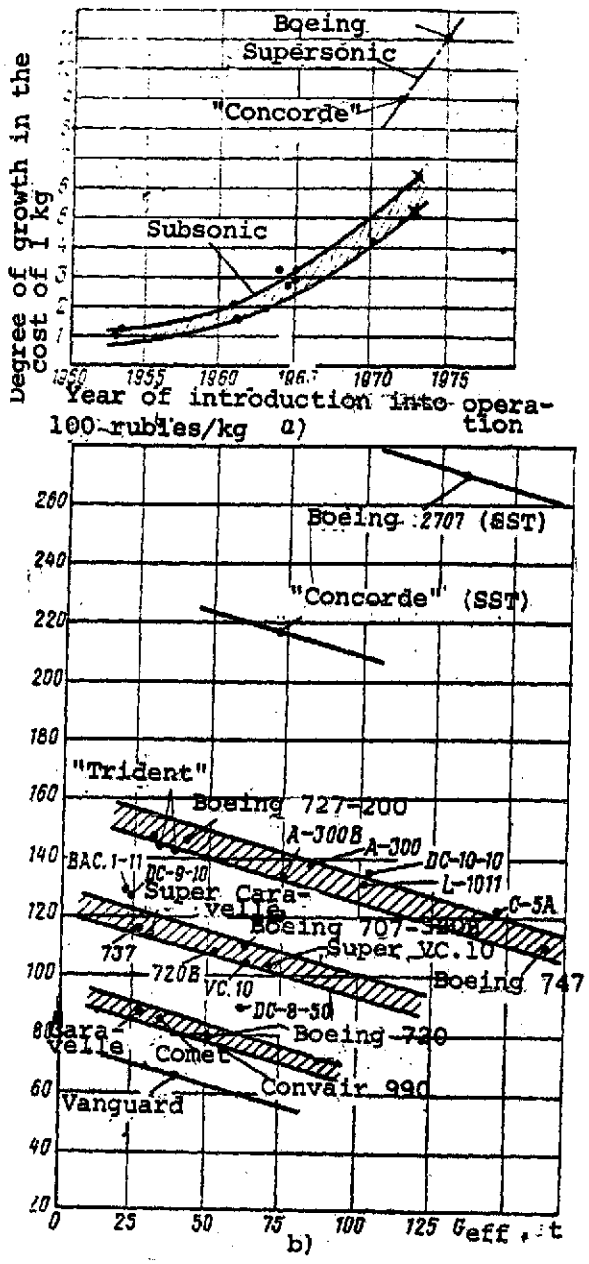

Fig. 1.8. Change in the cost of 1 kg of foreign airplanes: a. degree of growth (data from the 1953 level are taken as units); b. cost of 1 kg of airplane weight.

an increase in the dimensions of the airplane, a sharp increase in the number of available seats and some decrease in the coefficient of passenger loading during the initial period of operation. With an average annual value for this coefficient of 0.6-0.65, much free space remains, and from that there was a striving toward increasing cargo transportation, i.e. toward the maximum use of the volume of the fuselage and the load capacity of the airplane.

During the postwar years, i.e. during the period of piston aviation, the volume of cargo movements was not great, and the necessity for creating mixed or cargo airplanes for civilian utilization did not arise on a wide scale. Passenger airplanes were coping with cargo movements. True, some of them were refitted for exactly this purpose, for instance the Il-12D and the Il-14Gr.[11] The later increase in cargo flow was well matched with the development of large gas turbine airplanes whose economic operation required creation of increased baggage compartments. The further increase in cargo movements also required special cargo airplanes, which were at first created on the base of turboprop military transport airplanes, and later on passenger ones. The transport version of the "Britannia" airplane, developed in Canada and receiving the name "Canadair" might serve as an example of this. With a weight of 95,250 kg, its payload capacity reaches 30,000 kg. Cargo versions of turboprop airplanes also appeared during the present time on a base of those passenger

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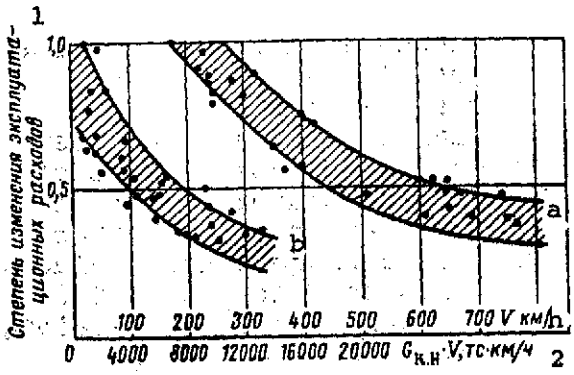

Fig. 1.9. Dynamics of operating expenses per ton km with an increase in: a. flight speed; b. hourly productivity. According to data from works [72] and [73].

Key: 1. Degree of change in operating expenses; 2. $G_{ef} \cdot V$, t·km/h

airplanes which are still not yet run out but cannot still compete with the newest jets. Conversion is accomplished by the installation of a large cargo door, and strengthening of the floor and fuselage constructions. This method of using equipment which is "spiritually" obsolete will apparently also be feasible in the future.

Modern jet passenger airplanes have fuselages in which the cross section is drawn out along the vertical (this section has received the name double bulb). In a large part of the turboprop airplanes, the cross section have the form of a circle. Many of the modern airplanes have cargo-passenger and cargo variations. This includes airplanes of almost all classes: intercontinental (DC-8F, Boeing 707-320C), medium-haul (Boeing 727C) and short-haul (DC-9C). They /35 appeared in approximately the same sequence -- from large to small. When the idea for creating rapidly convertible cargo-passenger airplanes arose, it was assumed that they would be developed only for use on medium- and short-haul airplanes, and that they would turn out to be unsuitable for long-haul and intercontinental ones, since to achieve the maximum range, every possibility was squeezed out of the plan, and the realization of this idea is connected with definite costs in terms of weight. Actually, cargo variations in this class have basically appeared with relatively widespread usage, but mixed ones also exist. Both of these variations have also been foreseen for the third generation airplanes (Boeing 747).

The dimensions and layout of the cargo-passenger airplane are selected on the basis of passenger aviation requirements. Their dynamic losses in this case are exluded, and weight losses connected with the possibility for conversion (under airport conditions) into the cargo-passenger or cargo versions are kept to a minimum. They are easily compensated by the possibility for using a rapidly convertible airplane for daytime flights in the passenger variation and for nighttime flights or transportation of cargoes in one direction, in the cargo variation, and on lines with a decreased passenger flow and in mid-season, in the cargo-passenger variation. This increases the use of the potential load capacity, but the economic effect is achieved only through the capability of these airplanes to compete with other forms of transportation in carrying industrial and other cargoes.

During creation of the cargo-passenger and cargo airplanes (on the base of passenger airplanes), the problem of mechanized loading and unloading the cabin and baggage compartments with minimum loss of time was solved. One of the solutions was that of containerized loading of baggage compartments and standard pallets for cargoes transported in the cabins. The deficiency in mechanized loading in containers is their relatively high weight. Manufacturing them out of composition materials must decrease weight losses. Various loading devices have also been developed, but introduction into operation of large cargo airplanes requires the further development of loading and unloading methods as well as new organization of these jobs, which have for a long time been the bottleneck in cargo transport aviation. An increase in cargo handling speed and a decrease in loading and unloading time will lead to a decrease in down time, which is a more important factor than flight cruising speed for this type of airplane.

It is understandable that the reviewed tendencies will be developed further. The careful handling of cargoes and shipping speed which are typical for air transport, together with future decreases in rates will increase the role of cargo shipments on third generation airplanes. Another thing is becoming clear. In the development of air cargo transportion, it is very likely that not only of the newly appearing types of passenger airplanes has created such technical possibilities as the aerobuses and giant airplanes. Their fuselages, with round and very large sections in which the part occupied by passenger seats comprises a small portion, have underfloor cargo compartments available in large volume and large baggage shelves above the seats. It is interesting that with an increase in the number of passenger seats onthe Boeing 747 by 2.5 times (as opposed to the Boeing 707), the volume of baggage space has increased by 4 times. This situation, as well as the cargo-passenger and cargo variations of aerobuses and gian airplanes, creat a leap in the growth of cargo transport volume which is apparently no less than that in the growth of passenger movements. /36

The number of cargo-passenger and cargo airplanes (based on jet passenger airplanes) built abroad reached 200 units in 1969. It is projected that their number will double in the beginning of the 1970's. This comprises a significant fleet of the new type of airplanes, which are apparently a connecting link between passenger and specialized transport airplanes[11]. It is appropriate, therefore, to recall the characteristics and peculiarities in the development of transport aviation, which by its intention closely adjoins the passenger airplane class. Its development was at first based on the best models of passenger airplanes. An example of this is the Il-12D paratroop transport airplane, which was widely used in the national economy at the North Pole and in the Antarctic.

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[11] By "transport" we mean airplanes designed only for carrying cargoes of various types (civilian and military).

In the USA, the C-135 transport airplane was developed on the basis of the Boeing 707. After that appeared specialized transport airplanes with turboprop engines, such as the An-12 (USSR), Douglas DC-133 (USA), "Belfast" (England), and others, and later the cargo giant An-22 "Antey," which preceded the appearance of similar machines abroad. The layout of these airplanes differs from the layout of the majority of passenger airplanes in the high positioning of the wing, the large dimensions of the fuselage cross section and the equipment grouping in the chassis. For development of transport aviation, just as that of passenger aviation, a constant and abruptly-moving growth in the dimensions (or tonnage, Fig. 1.10) is characteristic. In rate of development, these airplanes lag behind passenger ones for a long time, but recent achievements in the area of aerodynamics enabled the creation of effective transport jet airplanes. These achievements include: improved takeoff and landing characteristics by means of complicating the mechanization of the wing and decreasing frontal resistance in cruise configuration, and in part by means of improving local aerodynamics. The widespread development of these airplanes, the specifics of their operation and the peculiarities in equipment grouping and design led to a situation in which the transport airplanes have moved off into an independent class. This also corresponds to their widespread usage not only for military, but also for civilian purposes. A peculiarity of transport airplanes is the lesser influence of speed on technical[12] and economic effectiveness by comparison with passenger airplanes. This led to the fact that they did not move away from turboprop engines as rapidly as did passenger airplanes, where they survived only one generation of airplanes. For transport aviation, this type of engine maintained its value for a longer period of time, and the single stage turbojet engines have not been accepted. Only airplanes with two-stage engines (Il-76, Lockheed C-141A and C-5A) proved to be capable of competing with the turboprops. This same reason (i.e. the lesser influence of speed) allowed the sweep of wing to be limited to an angle of 25°. Another thing should be noted. The specifics of technical requirements for transport airplanes, whose accomplishment is connected with significant weight losses, has also led to a special weight balance which differs from other airplanes. This change in weight relationships is connected, in part, with a change in some of the geometric proportions. Thus, the requirements for a center of gravity envelope[13] significantly wider than that for passenger airplanes led to a noticeable increase in the static moment for the horizontal empennage, which in turn led to an increase in the relative size of its area and weight. The weight classification of these airplanes differs with the appearance of a group of devices needed for operations which are directly connected to the type and dimensions of the cargo being

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12 For more detail see Chapter 18.

13 Connected with extremely varied cargoes and large cargo compartment dimensions.

landed and are generally included in the total weight of the landed cargo[14]. These devices, designed for loading, fastening and unloading are sometimes called operational equipment. They comprise the second component in the overall total weight of the landing cargo and comprise a relatively significant portion [78].

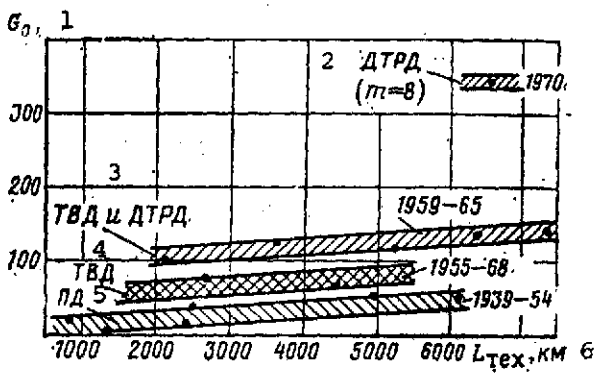

Fig. 1.10. The change in take-off weight (in t) for transport airplanes with an increase in range during the process of their development.

Key: 1. G_{max}; 2. double flow jet engine; 3. turboprop engines and double flow jet engines; 4. turboprop engines; 5. piston engines; 6. range, km.

2.6. Tendencies in the development of engines. Turboprop and single flow turbojet engines, with which jet aviation began are not presently used in subsonic passenger airplanes being developed. Turbofan engines with a low degree of by-pass (m) have also gone into history. Airplanes of the third generation are planned with turbofan engines having a medium and, primarily, high degree of by-pass. Regarding supersonic airplanes, the best engines have proved to be turbojets, with which the problem connected with conditions of the two modes of flight at subsonic and supersonic speeds is solved with a compromise. The difference between turboprop and turbojet engines consists in the final analysis of the fact that with the engine-propeller system, a large mass of air is accelerated to the attainment of a low speed, and in the turbojet engine, a lesser mass is accelerated up to a high speed. By-pass or turbofan engines combine these two principles of thrust with a large expenditure of air, and the fan is a tunneled or shrouded propeller (for more detail on the various types of engines see work [62]).

It is well-known that progress in civil aviation is determined primarily by achievements in engine construction. The appearance of turbojet engines led to an increase in flight speed and passenger comfort at the expense of an increase in fuel consumption and a significant increase in the level of noise around airports. The appearance of turbofan engines led to an essential decrease in both fuel consumption and noise level. An increase in the degree of by-pass enhances a further decrease in these amounts. The first jet engines appeared at the end of the 1930's, and at the beginnings of the 1940's, the first jet airplanes. After that,

[14] Other weight peculiarities for transport airplanes are spoken of in Chapter 10.

development of engines progressed rapidly for military airplanes. In civil aviation, turbojet airplanes only occupied the primary position in the second half of the 1960's. Over three decades, four generations of these engines appeared: two generation of turbojet engines and two of turbofan engines. The latter includes engines with a high degree of by-pass (m = 5-8).

Tendencies in the development of engines can be traced along graphs (Figs. 1.11 and 1.12), on which are shown the dynamics of the basic characteristics and the means through which engines are perfected. These characteristics include: specific attainable /39
single engine thrust (R), its specific weight (γ_e), specific fuel consumption (c_R), noise level, initial cost and cost of servicing. The values for these parameters are in dependency on the thrust and thermal coefficient of the efficiency. We recall that the thrust coefficient of efficiency is the name for the relationship of external work created by the thrust force of the engine to the increase in kinetic energy of the gas stream obtained in the engine. Regarding the thermal coefficient of efficiency, it is the relationship of the work performed by the reactive thrust per second to the fuel energy expended over that same period of time. Its value is proportional to the relationship of flight speed to specific fuel consumption and for airplanes flying near the speed of sound, lies within limits of 0.28-0.3. With M = 2, it increases up to 0.4 and has a tendency for further increase. During a review of the dynamics of the basic characteristics, it is easy to notice that the constantly increasing single engine thrust sharply increased with the transfer to a high degree of by-pass, with a jump of approximately 2-2.5 times, and now the possibility for further increase is practically unlimited. The specific weight of jet engines over a 20-year period (1950-1970) decreased by 2.5-3 times, specific fuel consumption decreased by 1.5 times, and over the entire period of their existence, fuel consumption decreased by 2.3 times (from 1.5 to 0.65 kg of fuel per unit of thrust). The change in these characteristics during the process of development has occurred by leaps-and-bounds. The first leap was with the appearance of turbofan engines, and the second was with the appearance of those with a high degree of by-pass. The latter leap amounts to 20-25%. The cost of the engine changed, the noise level /40
was reduced and reliability increased at the same time.

The basic means for improving engines include: improving the total degree of pressure increase (π_k), increasing the temperature of gases in front of the turbine (T), an increase which will improve the thermal coefficient of efficiency, and increasing the degree of by-pass (m), which affects the thrust coefficient of efficiency. The latter parameter has the greater influence on the design and characteristics of the airplane. An increase in m will lead to an increase in the thrust decline gradient according to speed, resulting in a significant passage of air through the engine. True, c_x of the engine does not increase with this. A significant improvement in the characteristics (γ_e and c_R) is

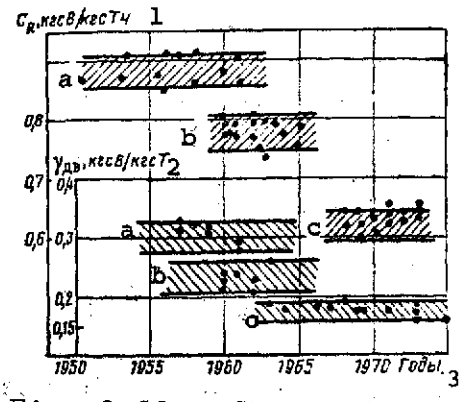

Fig. 1.11. Change in the specific weight of engines γ and specific fuel consumption c_R: a. turbojet engines; b. turbofan engines, $m \leq 2$; c. turbofan engines, $m > 5$.

Key: 1. c_R, kg weight/kg thrust·h; 2. γ_e, kg weight/kg thrust; 3. Years

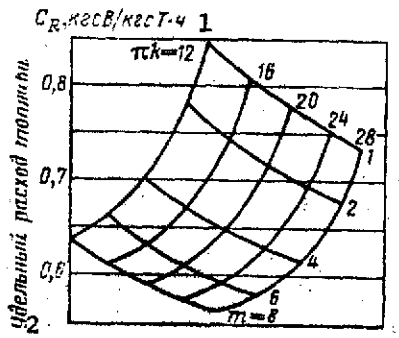

Fig. 1.12. Change in specific fuel consumption with a change in the degree of by-pass (m) and total degree of pressure increase π_k (according to data of work [75]).

Key: 1. c_R, kg weight/kg thrust·h; 2. Specific fuel consumption

achieved by simultaneously increasing the value of all the listed parameters, which are also enhanced by such factors as the introduction of titanium, the creation of heat resistant alloys and the development of methods for cooling the turbine. The further decrease in specific weight of engines is expected in connection with the promised widespread introduction of composition materials (which up to the present time have found only limited acceptance) and a great improvement in heat-resistant alloys. A study of engine development tendencies shows that the latter leap in their development will not lead to long-term stabilization, and that further increases in m, π_k and T are probable.

The effect of an increase in π_k and m on decreasing c_R is shown on a graph (see Fig. 1.12), which is set up under the condition T = 1300 K (with M = 0.8 and H = 11,000 m). The effect of a simultaneous increase in π_k, T and their optimum combination is illustrated in an example of data on three engines by the Pratt and Whitney firm (Table 1.2), published in work [72]. The last one of them is an engine of the future and its characteristics show a tendency toward further development.

An essential index in improving engines is the noise level. No less intensive work is conducted on the problem of reducing it than on improving characteristics. On single flow engines, noise reduction was achieved through the use of noise mufflers. Turbofan engines have allowed for these devices to be discarded. An increase in m will not lead to a reduction in noise level, but it will also not increase it. A further reduction can be achieved by affecting the source of the noise directly or by using sound-dampening surfaces. /41

TABLE 1.2. BASIC CHARACTERISTICS OF TURBOFAN ENGINES

Designation	JT3D	JT9D	JTND
Thrust R, kgf	8350	19800	45000
Degree of pressure increase π_k	14	24.5	40
Degree of by-pass, m	1.3	5	12
Pre-turbine temperature TK	1030	1360	1740

The design layout of engines is also being developed. In the 1950's, turbojet engines were the single-shaft type. After that, two-shaft engines were built, and by the end of the 1960's, the idea of a three-shaft layout appeared. In the two-shaft stage, a compressor with low pressure and a large diameter works at a lower number of revolutions by comparison with the high-pressure small-diameter turbine. Consequently, this layout allowed for the independent optimization of the compressor and turbine working rates to be conducted. The move to the three-shaft layout is a further development of this principle and is connected with the appearance of the large difference in the diameters of the fan (installed on a separate shaft) and other stages of the compressor. This solution increases stability of operation, simplifies construction, decreases cost and reduces the noise level.

The requirement for reliability, which serves as a measure of flight safety, now occupies a special place and exercises influence on operating cost (decreasing expenses on spare parts and servicing), on engine life and on regularity of flights (engine failures disrupt traffic flow and scheduling). Engine reliability is characterized by the number of failures on the ground and in flight. The effect of reliability on cost per ton-kilometer increases as the productivity of the airplane increases, since the cost of the delay in takeoff by 1 h will be higher in these airplanes. All this allows the assertion to be made that a higher initial cost of an engine is allowable if it is connected with increased reliability.

Historically, it has been surmised that engine cost increased with an increase in thrust, and the cost per unit of thrust rose only insignificantly[15]. At the same time, costs on tecnical servicing of engines have been systematically reduced (Fig. 1.13). The cost of technical servicing includes not only wages for labor

[15] Others assert that this has been significant (2-2.5 times over 10 years), and still others say that an increase in engine dimensions will lead to a decrease in cost per unit of thrust [89].

required for inspection and preventive maintenance but also the cost of spare parts. In connection with this, the new system of servicing, based on "condition control according to elements" represents a great deal of interest. The fact that it was developed over the course of 6 years shows the importance and complexity of the problem. This system provides for the constant measuring of a number of parameters in the fuel intake system and subsequent treatment of the results on computers. For this purpose, the /42
apparatus includes the flight recorder, instruments for acoustical and metallurgical analysis, spectrochemical oil analysis, ultrasonic monitoring and constant monitoring of the condition of the oil. The weight of the entire apparatus is 33 kg[16]. The system allows prediction of engine failures, and consequently, their repair or removal before the deficiency causes a delay or cancellation of a flight. The major advantage of this system is a reduction in the number of spare parts by approximately half[17]. The practice of adjusting servicing and repair over set time intervals has been reduced or eliminated. The new system has been called "technical servicing according to condition." Engine life has a great effect on the airplane's operating cost. At one time, it was counted in hundreds of hours, then it reached two to three thousand and it has now reached 10,000 and more. The further increase is connected with division of the engine into a number of easily replacable units with various life lengths. For instance, the surface area for an engine body may exceed 20,000 hours. It should be noted that different ideas on engine life exist. Some connected its value to the life of the main engine parts, and other, on the contrary, with the parts having the longest life. This is essential, but there are also other peculiarities with various interpretations.

The profitability of an airplane depends to a significant degree on the engines. The effect of its parameters are, however, not uniform for airplanes with various flight ranges. Thus, a decrease in specific fuel consumption on airplanes with a long flight range will lead to a greater economic effect than a cor- /43
responding decrease in specific weigh [62] or engine cost [80]. For short-haul airplanes, the latter factors will have a greater effect. Engine life and expenditures for its servicing are less connected with flight range -- they always have an essential effect. The cost of fuel, depreciation of engines and expenditures for their servicing reach 40-45% of all straight operating expenses for airplanes with a long flight range. The degree of the effect of these expenses can be illustrated by the following example: if,

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[16] Teck air, 1, 1069 [sic], p. 2

[17] In the beginning of the 1960's, the number of spare engines reached 42% of the number of engines installed on airplanes, and with this system, it has been reduced to 22%.

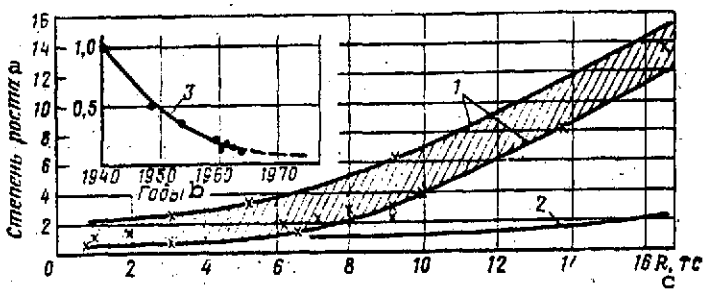

Fig. 1.13. Change in the cost of engines (1) the cost per unit of thrust (2) and expenditures on servicing (3) according to data from works [72] and [80]. Data from the initial engines are used as the base unit.

Key: a. Degree of growth; b. Years; c. 16 R, tons

with all parameters changing equally, a reduction in operating expenses due to a decrease in specific weight is taken as a base unit, they will be reduced by 1.3 times from a decrease in engine cost or expenses for servicing, and by 4.6 times by a decrease in fuel consumption. The relationship will be different for short-haul airplanes. Consequently, the power unit affects the dimensions of the airplane immediately through the thrust of the engines and tangentially through its characteristics.

Chapter 3. Tendencies in the Development of Air Transport

Tendencies in the development of airplanes as a means of transportation, i.e. the process of their improvements, were reviewed above. Here, the development of transportation as a system of air communications will be reviewed. The development of this system is characterized by a number of factors, chief of which are: an increase in the fleet, an increase in the volume of movements (connected with an increase in the fleet as well as with an increase in the productivity of each airplane), an increase in the degree of usage for each airplane (an increase in the annual average flight time) and, finally, as the summary index, a decrease in the cost of operations.

3.1. The increase in the airplane fleet. The high rate of introduction of jet airplanes into operation, i.e. the rapid growth of the fleet, was observed in the 1960's. For instance, a fleet of 116 countries belonging to ICAO, over 10 years (from 1958 through 1967) increased by 35% (see Table 1.3). The major factor is not, however, the growth of the overall fleet, but the change in its structure and the increase in overall productivity which increased by 4 times during this time, regardless of the fact that, by the end of the decade, a significant part of the air fleet of these countries consisted of obsolete airplanes with piston engines. An essential redistribution of transport capability according to airplane types occurred. The specific weight of movements on airplanes with piston engines dropped from 88 to 5%, on airplanes with turboprop engines it increased from 12 to 19%,

and then dropped to 11%, and on airplanes with turbojet engines it increased from 0 to 84%. During this period, piston airplanes were replaced on all international and, to a significant degree, on internal major lines.

Out of the total number of turbojet airplanes ordered (at the end of 1967) 82.5% were for passenger airplanes and 17.5% went for cargo and mixed (cargo-passenger) ones. The distribution according to classes is no less interesting. It has already been recounted that the massive development of passenger airplanes abroad began with the development of primarily four-engine airplanes weighing over 100 t. By the end of this period these airplanes comprised 49% of the total number of all mentioned types of airplanes ordered, three-engine medium-haul airplanes comprised 22% and two-engine short-haul airplanes comprised 29%. After that, orders for airplanes of the two latter classes predominated.

TABLE 1.3. SIZE OF THE AIRPLANE FLEET AND ITS STRUCTURE ACCORDING TO WORK [81]

Airplanes	in 1958	in 1967 (not counting those ordered)	in 1967 (counting those ordered
Passenger airplane fleet	4604	6229	6968
Turbojet	12 (0.3%)	2206 (35%)	2831 (40.5%)
Turboprop	418 (9.0%)	1335 (21.4%)	1449 (20.7%)
Piston	4174 (90.7%)	2688 (43.2%)	2688 (38.8%)
Of which DC-3's comprised	1480	1000	1000
Cargo and mixed			
With turbojet engines	—	355	587
With turboprop engines	—	62 } 6.3%	63 } 15%

By this time, medium-haul airplanes with turboprop engines (the Bristol "Britannia" and Vickers "Vanguard" of England and the Lockheed "Electra" of the USA) were removed from production. Orders continued only for short-haul airplanes (with turboprop engines) of the Fokker F-27 "Friendship" (Holland) type. Attention was also called to somewhat of a decrease in the rate of growth for the airplane fleet, which can be explained by a qualitative change in available technology, through which a greater volume of movements can be accomplished with an essentially smaller fleet. An increase in orders for cargo variations of passenger airplanes was observed at the same time. Tendencies in the development of air transportation are fully visible from Table 1.3, where the quantitative relationship of the airplane fleet is presented. This table includes airplanes weighing more than 9 t.

This is the way air transport developed in the first decade of its refitting with jet equipment. Projections for its further development in the second decade, i.e. over the period up to the end of the 1970's, are based on analysis of the increase in passenger flow.

The increase in the airplane fleet, just as in passenger movements will occur primarily due to the introduction of wide fuselage airplanes into operation. It is expected that by 1980 their number abroad will increase from 96 (in 1970) up to 2475. This number includes 700 short-haul twin-engine (250-300 seats), 775 medium-haul three-engine (350 seats) and 600 of their long-range modifications, and 400 intercontinental four-engine (up to 500 seats). Besides this, evidently short-haul modifications of three-engine airplanes with stretched fuselages and with passenger seats increased up to 500-600 and greater will appear. /45

Airplanes with less passenger capacity for short and medium lines having 150-200 seats (numbering up to 800 units) and for local lines having 40-100 seats and numbering up to 2000 units are also required. A significant part of these machines will consist of modifications of second generation airplanes with standard but stretched fuselages.

3.2. The increase in air movements observed during the period of piston aviation became particularly noticeable after the introduction into operation of turboprop and turbojet airplanes (Fig. 1.14). This occurred, as was noted, due to the increase in the productivity of the new airplanes and, to a lesser degree, due to expansion of the fleet. A change was also observed in the rate of annual movement increase, with its average annual value nearly 15% over a 10-year period (1959-1968)[18]. Looking at large time segments, the volume of movements increases fourfold every 10 years. However, by the end of the 1960's, a tendency toward deceleration in the rate appeared, and is also expected in the future (see Fig. 1.14) with a constant and significant increase in the volume of passenger movements. The reason for the decrease can be seen as the fact that the rate of growth, counted in percent, represents a large value at the present time. In order not to allow a further decrease, a sizable fleet of even more productive airplanes of the air bus type is required. A similar growth rate will bring air transport to the leading position (among remaining types) in volume of movements in the 1980's. /46

One of the characteristic peculiarities in the development of air transport consists of the periodic appearance of divergences between demand and supply in the number of airplane fleet seats, and this is explained by the comparatively smooth increase in demand of 12-15% per year and the surging character in the increase

[18] "Flight," 9.1, 1969, p. 48.

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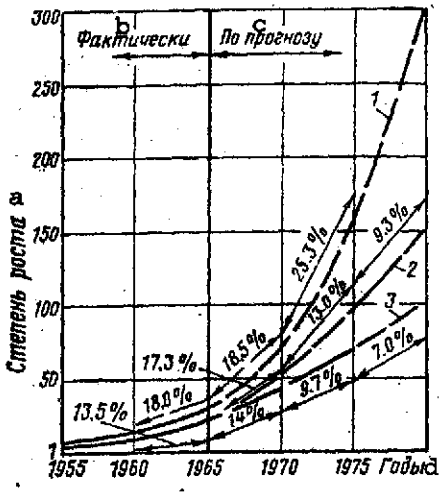

Fig. 1.14. Change in the volume of passenger and cargo aviation movements in the ICAO countries and the rate of their growth (according to data from work [73]). Data from 1955 are taken as the unit. Average annual increase in: 1 - cargo movements; 2 - passenger movements; 3 - average annual rate of increase in movements.

Key: a. Degree of increase; b. Actual; c. Projected; d. Years

of available seats. The leaps correspond to the introduction into operation of a new generation of airplanes, usually with a significant increase in passenger seating capacity. The divergences (zones A on Fig. 1.15) lead to underusage of the total passenger capacity and, consequently, the load capacity of the airplane fleet. The greatest degree of this will occur with the massive introduction of air buses, although their large cargo compartments will help to fill the breach formed in cargo movements. The graph presented is a simplified diagram which illustrates only the essence of this situation. In actuality the matter is more complex. For instance, periods exist which are distinguished by their agreement between airplane dimensions and the volume of movements (section a on Fig. 1.15). Changes in the coefficient of passenger loading (or utilization of the number of passenger seats) also has a staggered character. Its value decreases, sometimes smoothly and sometimes by leaps in precise correspondence to the character of the curve representing the number of available seats. For instance, during the period of one of these leaps in 1957-1961 (section b) the average number of seats in an airplane rose from 74 to 124, and the dimensions of the airplane almost doubled, so that the coefficient of passenger loading on the North Atlantic routes decreased from 0.67 to 0.51.

The introduction of air buses into operation must lead to a subsequent decrease in operating expenses per ton km. In the ICAO, it is projected that they will decrease by approximately 2% per year, as the result of which, they will decrease by 23% by 1980[19]. Fares for movements will probably have the same tendency. It should be noted that increases in movements on lines of various lengths are not uniform. At the end of the 1960's, when short-haul airplanes were widely developed, the volume of movements over /47

[19] "Aeroplane," 4.9, 1968, p. 8

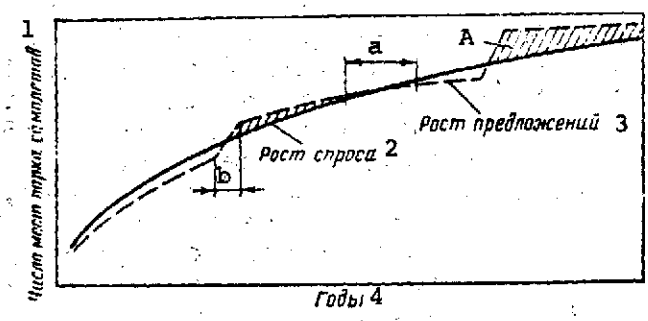

Fig. 1.15. Growth in supply and demand for the number of seats in the passenger fleet.

Key: 1. Number of seats in the passenger fleet; 2. Increase in demand; 3. Increase in supply; 4. Years

distances less than 1000 km in, for instance, the USA comprised 50%[20]. The increase in air movements across the North Atlantic, which remains one of the areas on the earth with the most intensive air communication is also an index. It comprises over 12% of the total volume of foreign movements[21], and marine shipping is steadily declining.

Cargo movements on turbofan airplanes began somewhat later due to the high cost during their first period, but the rate of their growth has proved to be higher and reached an average value of 20.5% per year over the first decade. They may increase up to 25% per year in the future (a preliminary reduction of up to 16% is allowed during this) due to the introduction of air buses and giant airplanes. With such a position (13.5% with passengers in the past and a reduction of up to 10% in the future) cargo movements in the beginning of the 1980's will exceed passenger movements or, on a smaller scale, half of the entire aviation transport volume will be used for shipment of cargoes. The volume of these movements will increase by 5-7 times in comparison with 1969. No similar increase has been observed either in industry or in transportation, and therefore air cargo is also called the "sleeping giant." The main freight turnover will be accomplished by the wide fuselage Boeing 747, DC-10, Lockheed-1011 and, possibly the L-500 airplanes. The latter can move up to 100 t of cargo at a time, which practically corresponds to the cargo capacity of four Boeing 707-320C airplanes (the cargo variation). Concerning an average annual reduction in movement cost and fares, it is projected that the amount of decrease will be 2-4%. The industries presented do not include mail shipments, prediction on which are considered to be more complex. We recall that with the development in the past, the annual increase was 12% per year. It is expected that this tendency will also be maintained in the future[22].

3.3. Factors on reduction of shipment cost. The effect of the technical and economic characteristics of the airplane on

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[20] Astronautics and Aeronautics, II, 1969.

[21] Interavia AAE, 10.10.1968.

[22] Aeroplane, 11.09.1968.

shipment costs was reviewed in section 2.4. However, the overall economic base for air transport is formed not only by these factors, but also many other operational factors affecting the amount of not only ancillary expenses but also direct ones. Analysis of tendencies in air transport development shows that beginning with 1959, /48 operating expenses and the size of fares for shipment have constantly declined, but not by any means evenly. Thus, the reduction occurred more rapidly on international routes than on internal ones with a significant increase in the percentage of annual reduction (3 to 1). This is connected with the peculiarity in the development of jet airplanes that the long-range ones, in which increases in speed and load capacity progressed significantly more rapidly, were created in the beginning. (We recall that fares, like prices on industrial goods, are the monetary expression of the cost of transport goods -- the movement of passengers and cargoes. Their amount is differentiated according to groups of air routes depending on the distance of the movements.)

One of the operational factors for reducing the cost of movements is an increase in flight hours. Therefore, the dependence between straight expenses and daily (or annual) productivity, also considering flight hours, is a more encompassing index. A high achievement in average daily flight would be 10-12 h, and in average annual flight would be 3000-3200 h. Among the factors having influence on the amount of not only straight, but also ancillary expenses, the length of continuous flight attracts attention. With its increase, not only the cruising speed increases, but there is also an increase in flight hours, the number of takeoffs and landings are decreased, the amount of airport expenses related to 1 flying hour decreases, and the life of the airplane increases inasmuch as the flying configuration is the determining one. In connection with this, the question arises on the advisability of using airplanes of a higher (according to range) class on shorter routes, i.e. on the optimum value for average route length. It is known that airplanes with a high productivity are often used on relatively short routes with a high density of passenger flow, which noticeably decreases the annual (for the fleet) productivity of flight. This question, just as many others, has its optimum solution only with consideration of actual conditions.

The overall problem of increasing the degree of usage for aviation equipment by means of increasing daily flight and the average length of continuous route include the questions of down time and removal of the airplane from the route. Their solution is connected with an increase in reliability and a decrease in the number of failures in the operation of all systems of the aircraft. A decrease in down time will lead to a reduction in the number of spare airplanes (whose cost is now extremely high) and, consequently, to an increase in the average flight for the entire fleet. Such problems as regularity of traffic and the coefficient of loading for the airplane also have a considerable effect on

reducing the cost of movements. Their solution is connected not only with operating conditions but also with many parameters of the airplane itself and the degree of perfection in its components and equipment systems. Finally, a serious factor in reducing the direct costs is the number of crew members. It is thought that a large number on the crew increases flight safety. However, automization of pilotage and equipment of ground servicing has allowed the crew to be reduced. It should be noted that the amount of the cost of movements on airplanes of the same type fluctuates. This is explained by the economic conditions of operation (particularly the wage level, cost of fuel, and scope of airport expenses), structure of the air line, number of airplanes in the fleet, arrangement of passenger airplanes, number on the crew and so forth. These conditions make comparative analysis of the economic effectiveness and competition capability more difficult. /49

3.4. Factors determining the coefficient of passenger loading (K_{pl}). K_{pl} is understood to mean the relationship between the number of occupied seats and the number of those available. Up to the present time, there is no single opinion on the effect this coefficient has on air movement economics and on the effect the various properties of the airplane have on its value. In operation, K_{pl} is determined as the average annual value on actual routes, either for a given type of airplane or for the fleet. Statistical data are considered for planning, but their value can be selected, varying the number of passengers and the frequency of flights, taking as the condition the volume of movements with consideration for its growth in the preceding years. For high frequency of flights with a combined passenger flow, an airplane with smaller dimensions is needed on the lines, which will lead to a higher K_{pl}. An airplane with larger dimensions is also more economical not only because it is more productive. It will carry the same number of passengers, but with a smaller number of takeoffs and landings, i.e. with a lesser amount of airport expenses and with less flying time. Not all factors are contradictory. For instance, the advantage of a high K_{pl} for the passenger consists of the possibility for reducing fares for movement, but this is also profitable for aviation, since it attracts passengers, promoting a further increase in K_{pl}.

A high K_{pl} increases the degree of usage of the available load capacity and productivity of the airplane and leads to an increased profitability even with reduced fares. The quantitative relationship is approximately thus. An increase in K_{pl} by 10% (i.e. from 0.6 to 0.66) allows fares to be decreased by 10% and with this increases profit by 1%, which is also significant. It turns out that an increase in K_{pl} is profitable, but up to known limits. Its low average value (0.6-0.65) indicates the large range of fluctuation in airplane loading (from 0.2-0.3 up to 1.0). Increasing the coefficient can be achieved by, for instance, decreasing the number of available seats (decreasing the dimensions of the airplane), but this will lead to a decrease in movements during the season, when K_{pl} reaches 1. Consequently, finding the optimum value for

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K_{pl} is a complex problem, whose solution depends on many factors. Besides the frequency of flights, which has already been mentioned, /50 the effect of the average flight duration also has an effect on the value of the planned K_{pl}. On short flights, where operating expenses are significantly higher than on long ones, K_{pl} must be higher, but at the same time, frequency of flights is also higher[23].

The tendency toward a decrease in K_{pl} during certain periods in the development of air transport is connected with a sharp increase in the number of available seats (Fig. 1.16 shows the change in K_{pl} during introduction of jet airplanes into operation). At the end of the 1960's, its value decreased to 0.6-0.65 and stabilized. (The same thing will occur with introduction of air buses into operation.) However, the threshold coefficient of loading K_{tp}[24] will decrease with this. A further decrease in it by 8-10% is expected with the third generation airplanes with high seating capacity. From the graph it is evident that during the years in which airplanes with turbojet engines were being introduced, the actual K_{pl} was lower than the threshold value. This is explained with the fact that productivity of the air fleet rose more rapidly than fares decreased, and therefore demand lagged behind supply. Reduction of fares was at first blocked by high operating expenses which were connected in part to low resources at that time. The change in the relationship during later years testifies to the increased profitability of air transportation.

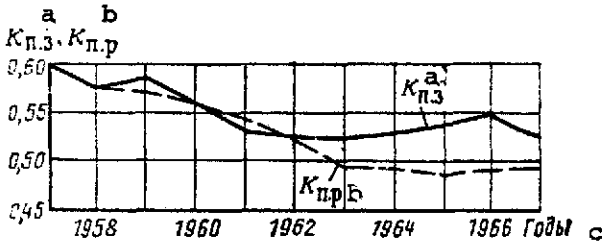

Fig. 1.16. The change in the actual values of K_{pl} and K_{tp}. According to data from "Aeroplane," XI, 9, 1968, p. 4.

Key: a. K_{pl}; b. K_{tp}; c. Years

3.5. Comfort and problems of noise. Questions of comfort are related to those problems in planning which are solved on the basis of a compromise between the tendency toward increasing the level of requirements and the striving toward increased economy. A high level of comfort will lead to an increase in passenger loading and with this will increase economy, but together with this, it will increase the weight of the fitted airplane, usually resulting in a decrease in the degree of usage of the volume of the fuselage, which has the opposite effect. A similar situation prevails with, for instance, questions of reliability, whose inherent effect increases economy, but in the face of the fact that /51

[23] This does not consider cases in which the frequency of flights is assigned.

[24] K_{tp} corresponds to the threshold of profitability (see 2.4).

with it the design is usually made more heavy and economy is reduced. In summary, the effects are positive.

The characteristics determining comfort of passenger seats are the width of the seats (between the armrests) and space between the rows. Together with the width of the aisles, they determine the floor area belonging to each passenger. This value is accepted as a parameter of comfort. Another factor appears in combination with cabin height, and that is evaluation of the volume belonging to each passenger [62]. While the first of these determines the width of the fuselage, the second determines its remaining dimensions.

The comfortable seats accepted for airplanes of the second generation, along with the low noise level, effective air conditioning, esthetics of the cabins and interiors done in a style of "pleasant simplicity," and outstanding service and feeding of passengers have all led to a category of an international standard. Therefore, questions of comfort ceased to be disputed at a certain time. The interior of wide-fuselage airplanes became a problem. The search for a proper number of seats in one row showed that installation of ten seats was permissible only for short flights and their optimal number must not exceed 8-9.

The arrangement of cabins with two wide longitudinal aisles and a large number of cross aisles, the spaciousness of the high seating compartments (Fig. 1.17), the free placement of the seats which are of an improved design and somewhat large dimensions, the higher level of comfort and, finally, large baggage shelves covered with flaps (Fig. 1.18), all distinguished the internal appearance of passenger cabins in the wide-fuselage airplanes. Besides this, /52
there are movie setups, tape recorders and television in the salons. On air buses there are spacious galleys located in the subfloor sections, and dispensing carts are raised from them to the deck on lifts (Fig. 1.19).

We recall that during creation of the second generation airplanes and their modifications, a striving toward increased density in cabin arrangement and a higher degree of fuselage volume usage was observed. In this manner, by means of lowering comfort somewhat, profitability was raised even with a simultaneous decrease in fares for tickets (with a decrease in seat class). During development of the third generation airplanes, the tendency toward /53
increase in comfort was apparent. A striving toward attraction of passengers, i.e. toward the increased demand necessary in connection with a sharp increase in the number of available seats can be seen in this (see Fig. 1.15).

Airplanes of each succeeding generation will become more perfect and more economical. There will also be something more distinguishing them from airplanes of the preceding generation. For instance, when airplanes with turboprop engines were introduced into operation, the passengers could notice a decrease in noise and

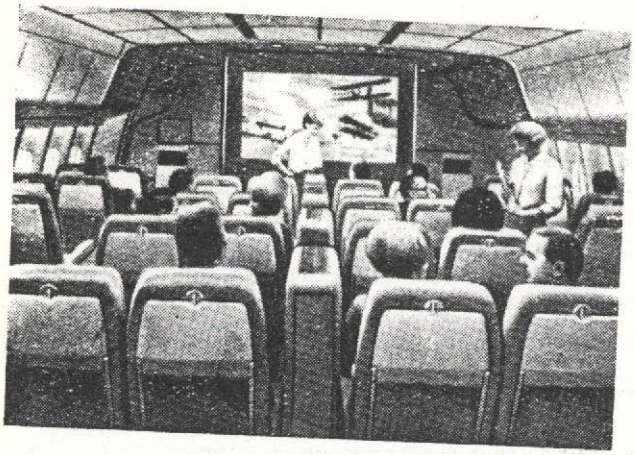

Fig. 1.17. Salon of a wide-fuselage airplane with movie setup.

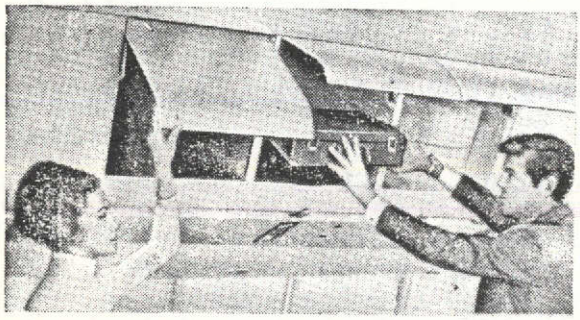

Fig. 1.18. Baggage shelves.

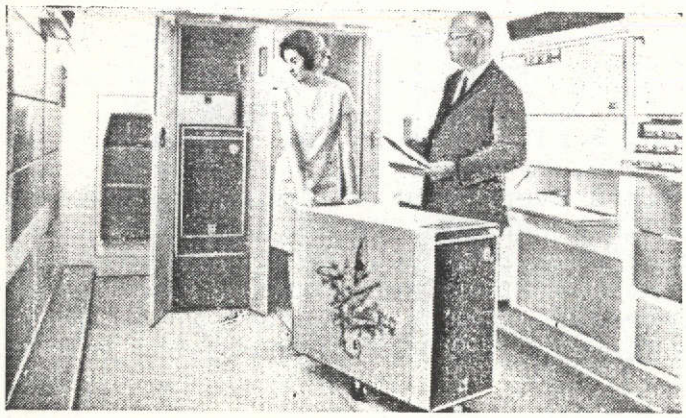

Fig. 1.19. Galley compartment in the subfloor section.

vibration. Airplanes with turbojet engines led to a significant increase in flight speed, and airplanes with enginesmounted on the tail to a decrease in noise. Wide-fuselage airplanes are distinguished by an essential increase in comfort.

Problems in noise reduction both in the cabin and on the outside continue to trouble designers. The problem of decreasing internal noise was solved by placing the engines on the fuselage. This led to heavier construction, although true, it was insignificant for air buses (see Chapter 15). The problem of reducing external noise was solved by installing noise mufflers on the engines. The result proved to be insufficient. After that, noise-reducing gondolas with long passages were developed. The decrease in thrust with them was very slight -- 0.1%, but the weight of the fitted airplane increased noticeably. Turbofan engines eased solution of the problem, but a tendency appeared toward increasing requirements for reduction of external noise. "At the present time, only a few modern three-and four-engined airplanes meet the proposed noise norms. These include the American Lockheed C-141, the Soviet Il-62 and the English VC-10" (Aviation Week," March 25, 1968).

In conclusion, we note that the tendencies in the development of passenger airplanes and

air transport reviewed here on the example of foreign equipment are also characteristic for domestic equipment, which is asserted by data of work [35], which is presented in Table 1.4.

TABLE 1.4. GROWTH INDICES IN THE SOVIET AEROFLOT

Designation	1968	1970	1975
Passenger turnover, billions of passenger-kilometers	59	72-75	110-115
Passenger movements, millions of people	61-62	75-80	115-120
Movements of mail and cargoes, thousands of tons	1600	2150	3000

Chapter 4. Airplane Modifications and Their Planning /54

4.1. Meaning of the problem. The primary direction in the development of aviation machinery, just as any other, is the creation of new models. This direction, however, conceals within itself a major contradiction which reflects the dialectics of machines. On one hand, the design constantly becomes more complex, saturation of the airplane with complex equipment systems occurs and development with consideration of preliminary studies of the required type dimensions occupies many years. As the resulf of this, the cost of the machines reaches an extremely high amount and also depends on its being unchanged and produced in high-numbering series. On the other hand, airplanes become obsolete rapidly and technical progress requires their constant renovation. The same thing is observed in the development of many other machines. This problem therefore bears a common character and has great significance for the national economy.

This contradiction will be eliminated with the new direction in the development of machines which is becoming ever more widely used, and that is namely development along a line of modifications which will lead to an increase in productivity for the machines. Therefore, any airplane, even the most successful one, must be improved in the future, i.e. its speed characteristics, range and commercial payload must be periodically increased. This will be achieved by improving its design or aerodynamics, improving or replacing the engines and, finally, increasing its takeoff weight, often in significant limits (sometimes up to 50%). The latter is an index of a significant increase in productivity on the one hand and the presence of potential possibilities on the other.

A regularity in development of modifications[25] reflects objective changes in air transportation lines, namely an increase in passenger flow density and the appearance of new lines. The types and methods of this development are naturally different and almost each airplane is developed in its own manner, however, study of this process allows observation of definite regularities whose understanding makes creation of an airplane which is adaptable for modification more easy.

One of the modern problems in design is the planning of modifications which is already conducted during the period of predrawing study. Although a large number of operating airplanes have their modifications, the problem of their design arose comparatively /55
recently and were fully solved only during planning of third generation airplanes. The creation of unplanned modification was in the past usually conducted by means of using the potential of engines (increase in thrust) or their replacements and the potential of airplanes (by using excess strength).

Problems in planning include selection of the type of modifications and the means for their development[26]. Their solution is not a simple task, and is based on technical and economic research. One form and method of development may prove to be preferable for airplanes of a single class (for instance, short-haul), while others would be preferable for other classes.

A second, no less complex part of the planning problem is the long-term projection of the degree of passenger space increase and productivity of the modifications. The complexity essentially consists of determining the increase in requirements over the course of many years of operation and achievement of reliability in forecasting.

Planning practice shows that the creation of airplanes with passenger seating capacity corresponding not to the first but to a

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[25] We remember that modifications refer to the process of modifying (without touching on the purpose of the airplane), both the airplane itself and changing its technical and economic characteristics to determine a higher degree of perfection. Modifications should not be confused with arrangement variations, which are considered to be peculiarities in operations on some lines or others but do not increase productivity of the airplane. Concerning cargo-passenger variations, they broaden the possibilities for using the airplane without changing its entire (transport) purpose.

[26] The agreed-upon forms of modifications differ depending on the character of change in flying characteristics (load capacity and flight range), and the methods of their development -- according to the amount of change conducted on the airplane, i.e. according to means for achieving higher productivity.

later period in their operation and which are consequently re-sized (in fuselage volume) at the moment the initial variations are introduced is not economically justified. The periodically arising necessity for increasing passenger seating capacity is satisfied with development of modifications corresponding to the situations accumulated on air routes. Meanwhile the creation period of for instance, modifications of short-haul airplanes does not exceed 2-3 years. The extremely changeable conditions also allow passenger airplanes to be included among machines which rapidly becomes obsolescent and will lead to the requirement for planning modifications during the initial stages of project development.

The widespread operation of air buses and giant airplanes, i.e. airplanes of the third generation will begin no earlier than the second half or the end of the 1970's. Consequently, movements will still be accomplished for a long time on second generation airplanes and, primarily, on their modifications. Besides this, third generation airplanes are already modified during the process of their planning, and therefore research on the problem of modification becomes ever more real.

In conclusion, the correctness of comparisons should be spoken of. It is natural that each newly planned airplane must exceed those in operation by its characteristics. However, the ones which /56 were later in the process of modification development exhausted their reserves and in this way achieved a high state of perfection. Airplanes in the state of planning as a rule take advantage of reserves, which somewhat decreases the effectiveness of the initial variation. In connection with this, the question sometimes arises on the correctness in comparing the latest modification of an airplane in operation with the initial variation of the one being planned for its replacement. In solving this problem, it should be kept in mind that this very comparison also defines growth in perfection in aviation development.

4.2. Periodicity and types of modification. Periodicity of modification, i.e. the period of introduction into operation of modified airplanes, is not identical for separate stages of development and for different classes of airplanes with gas turbine engines (Fig. 1.20). The development of piston passenger aviation also progressed along the line of modification, but it was episodic and insufficiently effective. Thus, for instance, the Super DC-3 modification of the DC-3, one of the first mass-produced passenger airplanes, appeared during the fifteenth year of its operation (in 1949). The Il-14, another mass-produced airplane, had modifications (Il-14P and Il-14M) distinguished by the long fuselage and number of passenger seats.

Periodicity of modifications is characterized in the final analysis by an increase in passenger movements. Modifications appear not only during the process of the airplane's development to correspond with an increase in the passenger flow on lines where

preceding variations are being operated, as happened with, for instance, the Il-18. The simultaneous planning of a single airplane in two or three variations is also encountered for routes with different densities in passenger flow. The question in this case is not one of simultaneous or sequential planning, but of the airplane's purpose. Modifications are usually developed with somewhat of a time overlap and then they prove to be more effective as the result of using the natural reserves which, as a rule, have a place but appear only during the process of testing.

The creation of airplanes with increased productivity at the same speed as the appearance of modification (see Fig. 1.20), is neither possible nor economic. The creation periods for airplanes are relatively long and increase constantly, which is tied to increasing complexity in technical problems and also with the difficulties of studying the airplane market and air line requirements. Thus, "the airplane building cycle (from the beginning of planning to the beginning of serious productions) during the 1940's averaged not more than 4 years, and in the 1960's, it grew up to 8-9 years" [27]. It is true that somewhat of a decrease was observed in recent years, but this can be explained by the accumulation of experience, the development of a material base and widespread usage of computer equipment. Concerning the economic side of the question, the development of modifications, including not only lengthening of the fuselage but also the use of new engines, turns out to be many times cheaper than the creation of a new airplane. The decrease in cost of movements which occurs with this increase profitability and promotes a rapid return of the expenditure for creation of the modification. /57

Types of modifications are distinguished by their character and the results of changes in flying and technical data. In some airplanes, passenger seating capacity (n_{pax}) and payload capacity (G_{cp}) increase with a decrease in or maintenance of the flight range (see points c and c' on Fig. 1.21 in comparison with the initial point b). In others, on the contrary, range is increased with maintenance of a constant n_{pax} and G_{cp} (point d). In still others, both occur (point e). An example of this latter case is the Douglas DC-8 and its three modifications: the DC-8-61 (point c), DC-8-62 (point d) and DC-8-63 (point e). It is also possible to discern other forms of modifications which expand the possibilities for using the airplane, for instance in the cargo variation with an increase in commerical payload capacity sometimes by 50 to 100%. The change in characteristics is achieved as a means of modifying operational airplanes and also as a means for simultaneously planning airplanes in two variations: "near" (for short routes) with a large number of seats and with a stretched fuselage and "far" with a shorter fuselage and correspondingly, a fewer number of seats and lower design weight. Similar planning

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[27] E. H. Heineman, RAS No. 650, II, 1965.

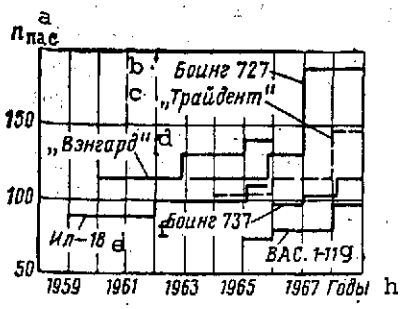

Fig. 1.20. Change in the number of passenger seats with modification of airplanes, characterizing their periodicity.

Key: a. n_{pax}; b. Boeing 727; c. "Trident;" d. "Vanguard;" e. Il-18; f. Boeing 737; g. BAC 1-11; h. Years.

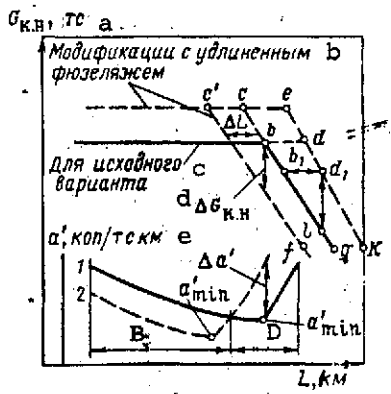

Fig. 1.21. Change in the commerical payload characteristic (G_{cp}) according to range (L) with modification of airplanes.

Key: a. G_{cp}, tons; b. Modifications with lengthened fuselage; c. For initial variation; d. ΔG_{pl}; e. a', kopecks/t km

is considered to be progressive for airplanes of different classes, from short-haul to intercontinental, since an airplane which is produced in two variations possesses significant potential for growth and a wide range of usage. An example of similar planning with us is the Tu-154 [19, 35] and the DC-8-60 abroad. /58

The expediency of this solution is determined by the fact that beyond the limiting value for range (point b), payload capacity drops sharply. During a flight with full fuel tanks (at maximum takeoff weight), it comprises no more than 40-50% of the limiting value (point g). The smaller this relationship, the greater is the maximum commercial payload weight and the higher the degree of wing volume usage. As a result, an airplane on flights corresponding to its maximum range or close to it will accomplish the flight half empty but relatively heavily loaded by its large and heavy fuselage. This deficiency will increase along with an increase in passenger seating capacity. We noticed that the weight of the part of the fuselage which is not used on long flights is commensurate with the size of the commercial payload transported in this case. For instance, increasing the weight of the airplane by lengthening the fuselage the distance required for placing one row of six seats is approximately equal to the weight of six passengers with baggage.

This allows the following conclusions to be drawn.

1. Operating airplanes with stretched fuselages on routes corresponding to the maximum fuel reserve is not economic (zone D on Fig. 1.21)[28]. 2. One of the

[28] Zones B and D are defined by a perpendicular dropped from the point of intersection of the two curves (1 and 2) of movement cost (a'), which correspond to the two variations of the airplane -- the initial one (1) with a short fuselage and the modification (2) with a stretched fuselage.

features of a modification with a stretched fuselage is a loss in range (ΔL) with G_{cp} = const or a loss in commercial payload ΔG_{cp} with L = const in the calculated instance (Fig. 1.21).

During the early period of jet aviation development, modifications of first generation intercontinental airplanes of the Boeing 707 type appeared. Their development moved with an increase in flight range, which corresponded to the appearance of new long distance routes. The passenger seating capacity of these airplanes remained almost unchanged, while on medium-haul airplanes (of the Il-18 and Tu-104 type) it was changed with a maintenance or increase in flight range. Modifications of short-haul (of the Tu-134, BAC.1-11, DC-9 and Boeing 737 type) and medium-haul (of the Tu-154, Boeing 727 and "Trident" type) airplanes in the second generation were rapidly developed, primarily along the lines of increasing passenger seating capacity, which was caused by a sharp increase in the density of passenger flow. (True, a multiseat modification of the DC-8-61 intercontinental airplane appeared during this time.) Consequently, the different classes had their own different types of modifications, and the greater the range possessed by the airplane, the less the degree of passenger seating capacity increased and the greater the flight range (Fig. 1.22).

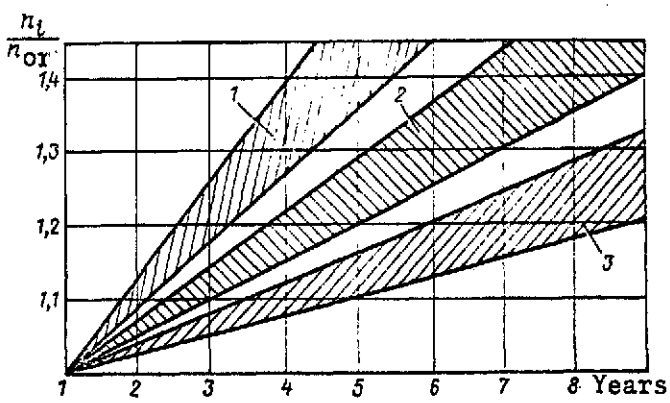

Fig. 1.22. Relative increase in the number of seats on later modifications n_i by comparison with original variations n_{or} as a function of years of operation of short-haul (1), medium-haul (2) and intercontinental (3) airplanes.

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While the appearance of modifications with increased range is connected with the development of long-range air communications, the appearance of multiseat modifications reflects the growth tendency in the volume of movements by means of increasing the dimensions of the airplane, and not the size of the fleet.

The increase in the number of passenger seats in first generation airplanes occurred through increasing the density of the layout without increasing the length of the fuselage. Expressed through floor area per single passenger, this density decreased from 0.93 to 0.68 and 0.55 respectively for the new seats which appeared: tourist class immediately behind

first class, and economy class behind that. Their new design allowed leg room between seat rows to be decreased and their number in one row to be increased (Table 1.5).

TABLE 1.5

Designation	Il-18A	Il$_B$18	Il$_V$18	Il$_D$18	Il-18Ye
Leg room between seats, mm	1020	840	810	750	750
Number of seats in one row	5	5	5	6	6
Number of passenger seats	75	89	100	110	122

The takeoff weight and power of the engines increased with the significant increase in the number of passenger seats, especially with a simultaneous increase in flight range (Il-18D). In these models, besides this, equipment systems were added (primarily air conditioning for the purpose of maintaining the level of comfort). The dimensions of the airplane and its design remained unchanged. As was noted, another type of development, connected with an increase in the length of the fuselage was characteristic for successive generations of airplanes of this class. The Boeing 727, DC-9 and other American airplanes had similar modifications. The English "Trident" airplane underwent both kinds of modification. /60

An increase in flight range is also achieved by various methods: an increase in the quantity of the fuel system, installation of more economic engines or both of these simultaneously. Fuel system volume can be increased either through the unused volume in the wing center (Il-18), the volume in the vertical stabilizer (Super VC-10 and Il-62M), or by means of installing suspended tanks ("Comet"). In this manner, increasing the technical and economic indices with modifications can be achieved through various means.

It should be noted that with airplane modifications, due to the increase in maximum range (points g and k on Fig. 1.21) an essential economic effect is achieved simultaneously due to a significant increase in commercial payload (ld_1) and the number of passengers carried on flights which are also within range of the original variation (ℓ) with a load which is less than the maximum. A somewhat different approach to economic analysis of similar modifications is also tied to this position. While in a comparative evaluation of airplanes of a single type according to movement costs it is necessary and usually sufficient to review its minimum value (point a'_{min}), this is insufficient to determine the increase in economy of a similar modification (bdk) of it. (With an increase

only in range and the same commercial payload (bd), the decrease in minimum cost is not great but possibilities for using the airplane are expanded.) The economic effect of this modification is determined by means of analyzing operations on actual routes with consideration for the increase in commercial payload (ld_1). A characteristic example of this is the Il-62M modification, in which the maximum range was increased by 13% (gk), which, generally speaking, is significant. The major achievement of it is, however, the 50% increase in commercial payload and the number of passengers transported on, for instance, the Tokyo-Moscow route.

4.3. Changes in parameters and characteristics. The creation of a modification is usually connected with a change in weight and other characteristics. Their quantitative changes are different and depend on the type of modification. Thus, the maximum takeoff weight with a change in the characteristic along curve bc (see Fig. 1.20) is maintained, and increases along curves bd and dk (by comparion with curve bg). The maximum landing weight of the airplane and the weight with zero fuel reserve increases in the first and second cases, but remains unchanged along bd and dk. An increase in takeoff weight will lead to an increased specific load on the wing p and to a decrease in the power-to-weight ratio $\bar{R}$, as /61 the result of which the takeoff and landing characteristics are changed. Thus, the balanced field length $БФЛ^{29}$ increases in the latter three cases and approach speed increases in cases c and e. This is justified for flights at maximum commercial payload at maximum range. On flights at a comparable range, modifications dk and bd will have a high specific load on the wing (by comparison with bg) and, consequently, an increased speed for approach to the landing.

The change in the basic parameters (p and $\bar{R}$) with modifications is shown on Fig. 1.23. The arrows on the curves indicate the direction of the change. The horizontal and vertical sections of the curves correspond simultaneously (with an increase in takeoff weight) to an increase in engine thrust or wing area. With this, the reduction is apparently the rule and the ascending curve is more likely the exception. An increase in wing loading and a reduction in the power-to-weight ratio on the later modifications are sometimes compensated by an increase in the degree of wing mechanization to maintain the takeoff and landing characteristics. The DC-9 can serve as an example of typical development in short-haul airplanes. It is true that wing area in one of the modifications was increased, and this is explained by the presence of small breaks on the corresponding curve. The reason for increasing the required БФЛ length (Fig. 1.24) and the approach speed are precisely the drop in $\bar{R}$ and an increase in p. The development of the "Caravelle" airplane went along the course of increasing the power-to-weight

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[29] We recall that the balanced length of a runway (БФЛ) is the distance from the starting point to the point at which the curves for the takeoff distance the distance of an aborted takeoff in the function V_1 intersect (V_1 is the optimum speed with failure of one of the engines.

ratio, and in the Boeing 707, after a ninefold engine replacement (with an increase in thrust almost every time), the power-to-weight ratio declined[30]. As a result of these modifications, the load ratio and productivity increased and the cost of movements decreased. The degree of change of the different characteristics is illustrated by an example of one of the modern medium-haul airplanes (Fig. 1.25). /62

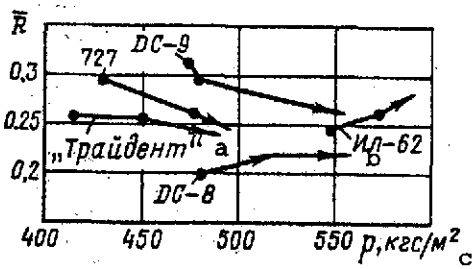

Fig. 1.23. Change in specific wing loading p and power-to-weight ratio $\bar{R}$ on a modification of passenger airplanes.

Key: a. "Trident;" b. Il-62; c. p, kg/m^2

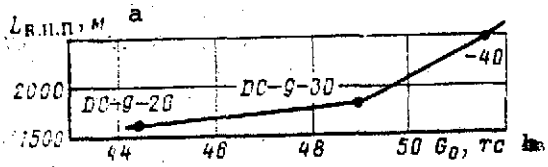

Fig. 1.24. Change in the takeoff and landing characteristics of a modification of a short-haul airplane.

Key: a. BFL, m; b. G_0, t

We notice that the weight characteristics of the airplane are changed during the process of operation not only with a modification. Thus, the takeoff and landing weight of medium-haul and short-haul airplanes are increased, due to which refueling can be avoided at intermediate airports on flights at maximum payload. In this case, their values increase due to the fuel discharged from the wing during flight. If a strengthening of landing installations is required, the problem is solved relatively simply (the gear design and braking installation are strengthened and reverse is modified). A similar solution is economically advantageous, since turn-around capability is increased and servicing time for the airplane is decreased. This tendency appeared comparatively recently in connection with an increased intensity of traffic. In airplanes of the classes mentioned, the relationship of the maximum landing weight to the maximum takeoff weight has now reached 0.9-0.95. It has decreased commensurately in airplanes with long flight ranges.

4.4. Types of planning. Methods for development of modifications in the study of planning questions are most

[30] In a process of modification, wing area was changed from 226 to 269 m^2 and that of the empennage from 46 to 58 m^2, while the weight of the fitted airplane increased from 53.5 to 61.2 t, and takeoff weight increased from 116.6 to 148.3 t.

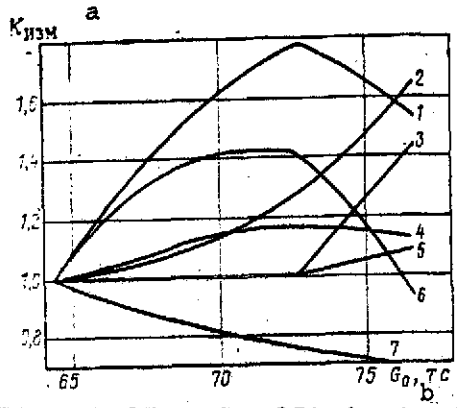

Fig. 1.25. Coefficient of change (K_{ch}) in productivity (1), commercial payload (2), number of passengers (3), load ratio (4), design weight (5), flight range (6), and cost per t km (7). Data from the basic variation are taken as the unit.

Key: a. K_{ch}; b. G_0, t

interesting and remain disputed, inasmuch as they are connected with the scope of reserves. It is well-known that three factors secure a long flying life for an airplane: a) high reliability and safety; b) economy and regularity; c) potential for development. It has already been noted that a large part of modern airplanes have modifications, but they were planned only during development of third generation airplanes, often with a significant change in dimensions and characteristics of the plane. For instance, fuselage lengthening by 15-20% (and in some cases up to 40%), increasing passenger seating capacity up to 40%, and takeoff weight (with consideration for maintaining or increasing flight range), up to 15-20% are provided for. /63

The planning of a modification consists first of all of imagining the overall appearance of the modified airplane and determining its basic parameters, characteristics and productivity, i.e. providing for (or establishing) the potential possibility for increasing the number of passenger seats, flight range, takeoff weight and engine thrust with the minimum (in the future) number of changes in the dimensions of the airplane. Planning modifications includes, as was noted, choice of types and methods for developing the airplane and solution of the problem of economically advisable reserves. A prerequisite for this planning is the study of conformities in the growth of passenger flow density and required frequency of flights in the future.

Two basic courses or two lines of development are differentiated -- extensive and minor modifications. It should be noted immediately that these lines are not connected with quantitative evalution of the results. In some cases, extensive modification can lead to a greater effect than minor, and in others, their effects will be equal. All of this depends on the formulation of the problem. When the question of modifications arises during the process of operating an actual airplane with a change in characteristics which was not foreseen during its planning, extensive modifications will lead to greater results than minor ones. If in the process of planning, modifications leading to definite qualitative changes (for instance, an increase in passenger seating capacity by 30%), then the scope of change with any modification (extensive or minor) will depend on the character of safety margins,

and in this case, both of these lines of development will lead to an equal final result, which was foreseen during planning.

Airplane modification can also differ in the relationship of their realization. In some cases, they are released into production upon removal of the initial variation, and in others (differing, for instance, in flight range), the initial variation remains in production. Another thing, however, is important: sometimes the character of modification allows for the changing (development) of airplanes manufactured before the appearance of the modification (and removed from production), and in others this is not allowed. Then, the airplanes produced earlier continue in operation in the initial version. This question can be reviewed during the planning period for the modification, when it is possible to accept one of the two aforementioned solutions, because it, like many others, hides a contradiction within itself. The development of the first variation with the purpose of bringing its effectiveness up to the level of the modified one appears to be /64
advisable. However, the additional reserves used for simplifying this work can reduce the economy of the initial variation. The modification planning process is, therefore, a constant series of compromise solutions between characteristics of the initial variation and possibilities for its modification in the future.

Turning to a preceding question, it should be stated that commonly acceptable definitions for the terms "minor" and "extensive" modifications have not yet been arrived at. It is, however, clear that such changes as increasing the length of the fuselage within limits defined by the landing angle (Fig. 1.26)[31], or exchanging engines for the purpose of increasing thrust or improving economy can be called minor modifications. A change in the wing with a significant increase in its area, usually connected with an increase in the tail assembly and consequently, with an increase of the load on the fuselage, is considered to be an extensive modification. The latter will lead not only to a large volume of design changes, but also to an expansion of programs in various laboratory, aerodynamic and flight tests.

It should be noted that in worldwide aviation practice, a strict delimitation of these two lines is not observed. In other words, it cannot be concluded that some airplanes are developed only along the line of minor modifications, and others are developed only along the line of extensive ones. Rather, airplanes which continue to be in operation will undergo both types of modifications. At first, they usually undergo minor modifications, and /65
then extensive ones, without excluding their later alternation in addition. The possibility for modifications -- minor or

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[31] If N_{st} is defined as the distance from the ground up to the engine, the reserve for increasing l_f will be greater with placement of the engines beneath the wing.

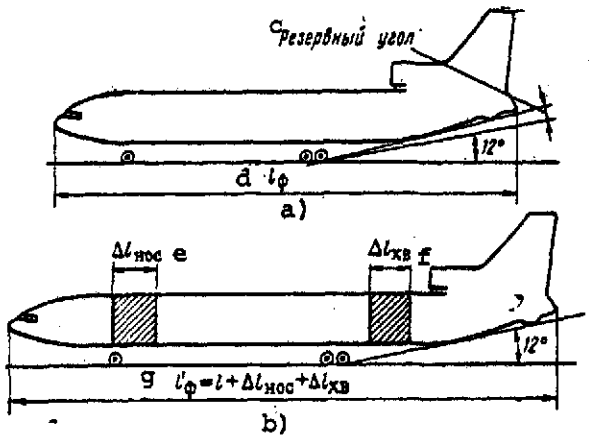


Fig. 1.26. A fuselage length increase, limited by the value of the landing angle: a. original variation; b. modified variations.

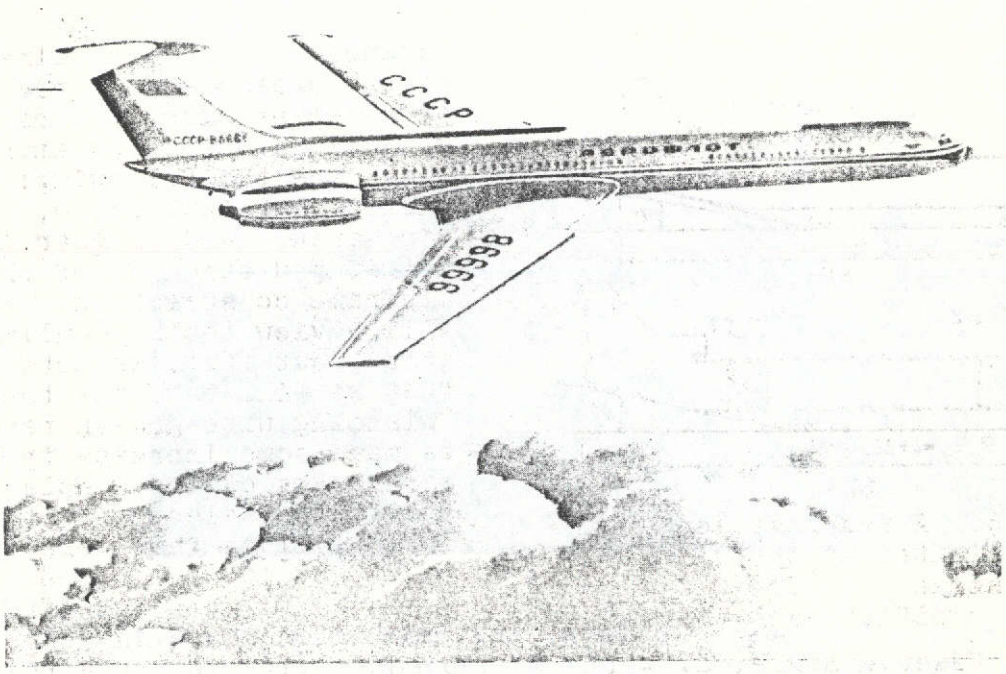
Key: c. Reserve angle; d. ℓf; e. $\Delta\ell nose$; f. $\Delta\ell tail$; g. $\ell'f = \ell + \Delta\ell nose + \Delta\ell tail$

extensive -- is determined by the presence (or creation) of reserves along several directions. Primary among these are the following: thrust-to-weight ratio, wing area, landing gear leg height and strength of the airframe construction. We will review their peculiarities, but first we note that we will take the term "planning with growth reserve" to mean some increase in the parameters of the airplane, i.e. their selection with some larger values than were necessary to obtain the assigned flight, takeoff and landing characteristics and productivity in the airplane.

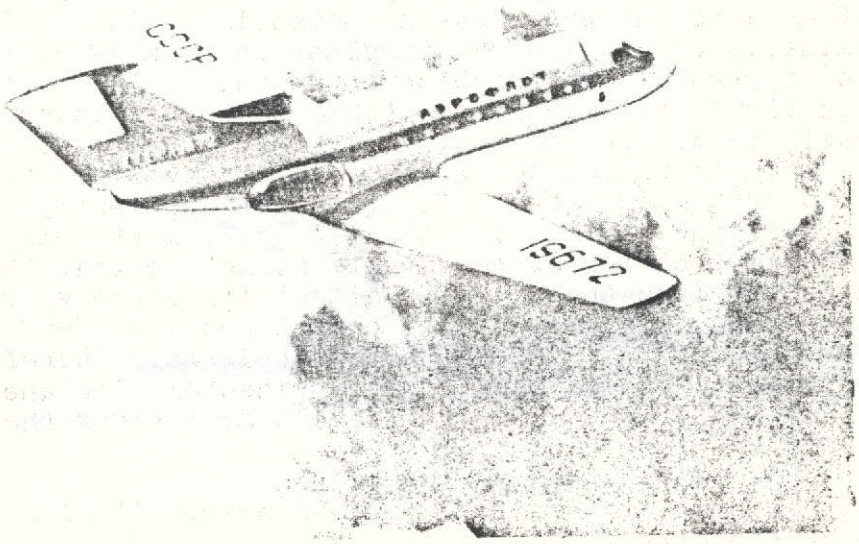
Whatever course of modification are selected, it is necessary to consider the possibility for their realization through minimum changes in the future. Reserves are needed for this, and they make the initial variation heavier. On the other hand, the striving toward the achievement of maximum effectiveness in the initial variation, excluding the tendency for providing reserves, can lead to the creation of an airplane which has no potential. It is already known that one valuable property of an airplane is usually achieved at the expense of partial constriction of another. It is impossible to create an airplane which is adaptable to modifications and simultaneously possesses the maximum effectiveness, just as the creation of, for instance, an airplane which would be impossible to lighten would be unsuccessful. The question apparently leads to determination of the minimum economically expedient weight losses which are due to creation of reserves. We notice that the smaller the airplane, the less these losses effect its economy, which can be explained by the high commercial output and low coefficient of increase for takeoff weight[32] in these airplanes. Therefore, it is apparently advisable to plan intercontinental airplanes without reserves, and with their subsequent development along the line of extensive modification.

The dimensions of a modified (and an original) airplane are determined by the size of the paying cargo, i.e. G_{cp} and n_{pax},

[32] For more detail see Section 9.4.



Il-62 airplane, flagship of Aeroflot's mainline routes



Yak-40 airplane, flagship of Aeroflot's local routes

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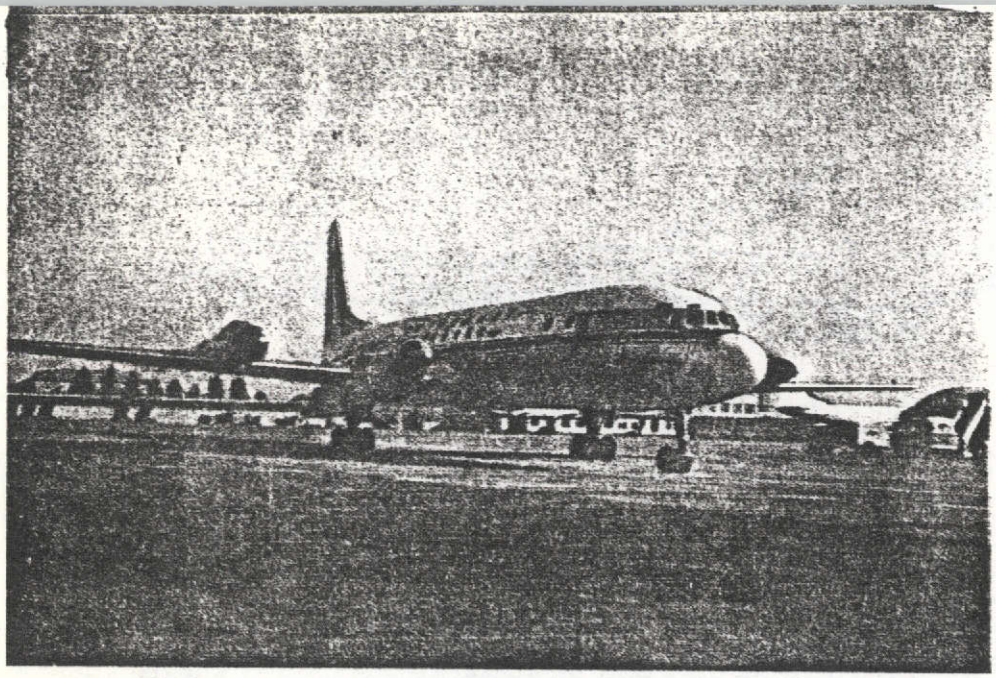
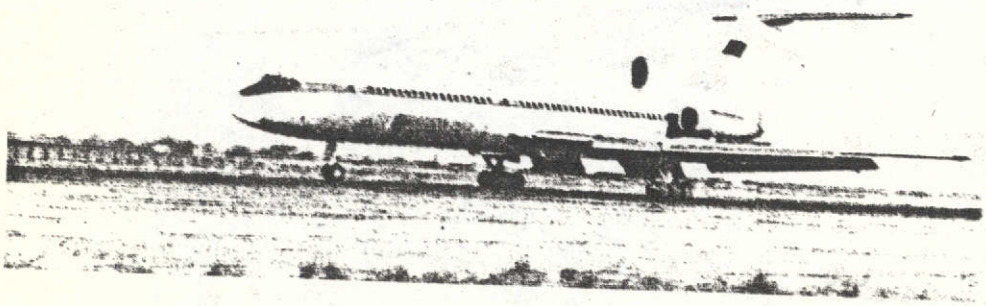


Il-18 with turboprop engines, the most massive of the first generation medium-haul airplanes.



Tu-154 with turbofan engines, second generation medium-haul airplane

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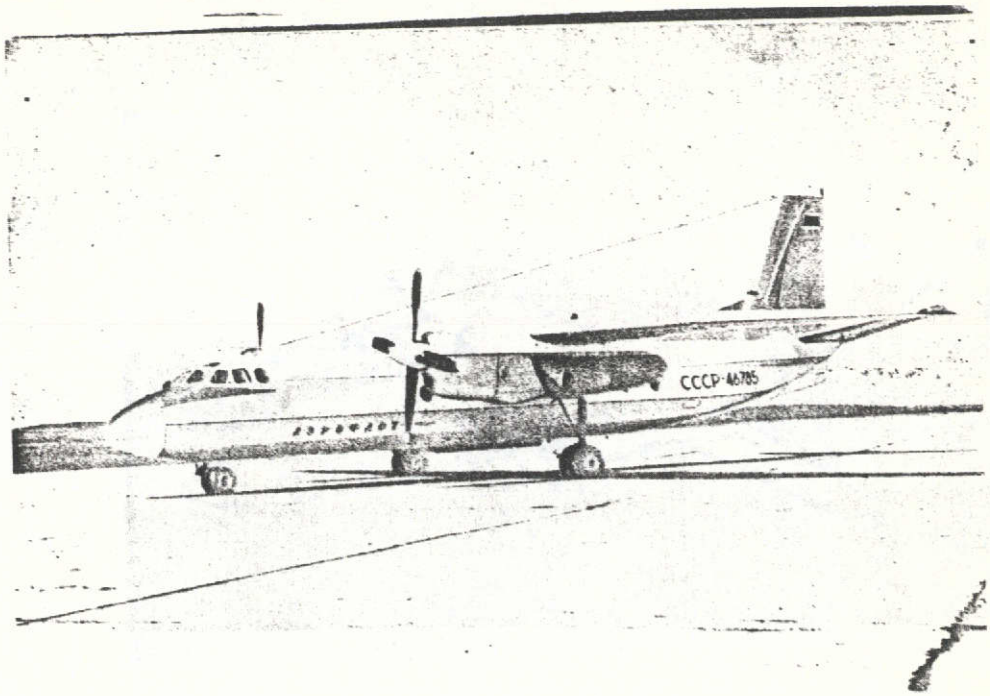
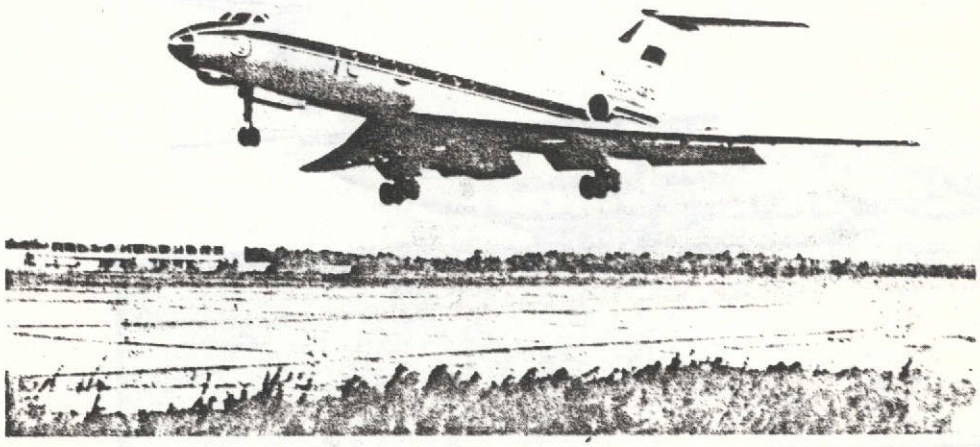


An-24 first generation two-engine turboprop airplane



Tu-134 second generation two-engine turbojet airplane

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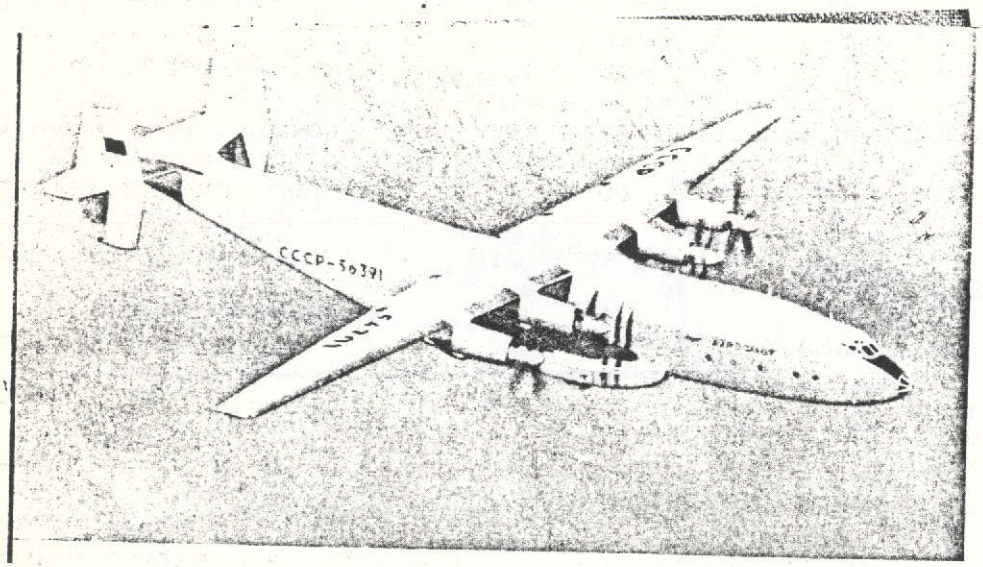
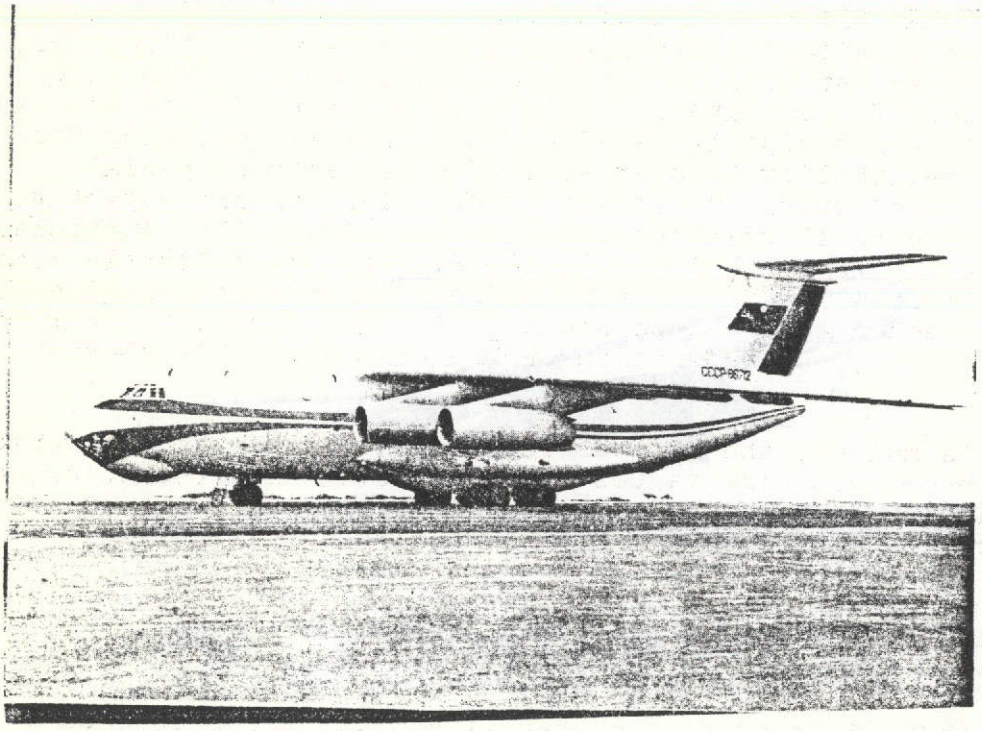


An-22 "Antey" transport (cargo) airplane with turboprop engines



Il-76 transport (cargo) airplane with turbofan engines

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flight range (L), cruising speed (Vcr), and takeoff and landing characteristics. The increase in commercial payload determines the dimensions of the required inserts in the fuselage. Solution of the problem of wing area and power-to-weight ratio depends on power settings for takeoff and cruising at a set flight level. This is true for an airplane with fewer than two engines. With the two-engine layout, the determining factor might turn out to be the power setting for an interrupted landing, when landing weight reaches 0.9 times the takeoff weight and also with the complex mechanization of the wing (decreased k_{ldg}) on an airplane with more than two engines.

It was noted above that changes connected with replacing the power unit might be considered minor modifications. However, increases in thrust are also accomplished without replacing the engines, inasmuch as they possess a potential possibility for increasing thrust. During the search for new methods, configurations were proposed in which the number of engines comprised 2.5 and 3.5, i.e. configurations with booster engines having less thrust than each of the main ones[33]. It can be used either during the course of the whole flight or during takeoff and landing. The latter is obviously the more advantageous, but the better form can be realized only on those airplanes whose full-sized engines satisfy the requirements in altitude characteristics for cruising of the modified airplanes with an increased flight weight without changing the flight level. /66

For modifications of short-haul and medium-haul airplanes, booster engines (starter accelerators), used on airplanes with vertical takeoff, may turn out to be satisfactory for takeoff and landing. They are distinguished by their low weight, easy servicing and reliability of start-up. The latter has special significance for providing an interrupted landing and departure for a second circuit when one engine has failed. The additional weight of the power unit in this case will be significantly lower than would a relative increase from the main engines. Besides this, it is decreased due to the possibility of eliminating the auxiliary power unit (APU), whose function can be assumed by the booster engine.

In this manner, the methods for increasing thrust are varied. However, to provide high values for the basic characteristics, also and including the economic one, a rather strict correlation between the engines and airframe is necessary. Also, if in the initial airplane this correspondence has been achieved, an increase in thrust for maintaining takeoff and landing characteristics with an increase in takeoff weight for the succeeding modification will

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[33] The first configurations with 3.5 engines were adopted on the "Trident-3B" airplane. The takeoff accelerator possesses a thrust equal to 0.45 of the thrust of a full-sized engine and a specific weight of 0.105. For more detail on this layout, see Section 7.2.

lead to a requirement to increase wing area because of conditions of cruising at an assigned altitude. As a result of the aforementioned, the question arises on the advisability of some increase (selection with a reserve) of wing area and a reserve in thrust.

It is known that engines, like airplanes, are modified, because with modification they possess the possibility for increasing thrust by means of increasing π_k, or T, or even m. Consequently, the potential increase in thrust can be planned during creation of the engines. Regarding some changing in the size of the wing, it will allow development of the airplane along the line of minor modifications. With an increase in takeoff weight on a modified airplane, such takeoff and landing characteristics as BFL length (L_{BFL}), speed gradient (V_y/V_2) and approach to a landing speed (V_{al}) are changed. The change, naturally, occurs to a lesser degree if thrust is increased and to a greater one if the same thrust is maintained. However, a wing area which is selected with /67
a reserve allows modified airplanes to be operated from airport of a given class and the set cruising altitude to be maintained. The initial variation will have somewhat better (than assigned) takeoff and landing characteristics available. Consequently, some resizing of the wing is also not without advantage for the initial variation of the planned airplane. At the same time, however, it is known that the higher the load on the wing, the more effective is the airplane as a whole.

An increase in the carrying capacity of the wing in the takeoff and landing configurations by means of mechanization allows area dimensions to be limited, but with this the advantages provided by the high coefficient of lift force are lost to a known degree due to complication of the construction, an increase in weight and aerodynamic resistance. Besides this, the problem does not consist of a simple increase in the maximum lift force, but of obtaining the maximum possible c_y with a simultaneous achievement of high aerodynamic qualities in flight.

One of the airplanes being operated at the present time can serve as an example of this. It has three-section flaps which occupy three-fourths of the wingspan, and eyebrow slots and Kruger panels installed on the leading edge. Due to this high degree of mechanization, $c_y = 2.5$ was obtained in the landing configuration, but with this the aerodynamic quality did not exceed 5, while with limited deflection of the flaps during flight $c_y = 2.0$ and the aerodynamic quality can reach 10. Another example might be the Fokker F-28, where in addition to complex mechanization, an increase in wing area was used, so that with a moderate lengthening, the same advantage was obtained, but with a smaller increase in weight and without complicating construction. In this case, the alternative choice of an extensively mechanized wing or a wing with a larger area was made with consideration for actual conditions.

The most expedient degree of wing mechanization can be found with weight equivalent, which are true for airplanes with definite values for the power-to-weight ratio and wing loading. The approaches to solution of this rather common problem can be various. One course, proposed by A. A. Badyagin [3], consisted of setting the weight equivalent of the change in c_y at 0.1. It shows the limit of advisable weight losses. Another means for an immediate solution consists of determining the possible increase in takeoff weight by means of increasing mechanization under the condition of maintaining the BFL. It is understandable that part of the increase in takeoff weight will be covered by the increase in design weight which is connected with mechanization of the wing (with consideration of the coefficient of increase[34]). But its largest part will allow a weight increase in commercial payload or fuel, which must also support the economic effectiveness in increasing the mechanization of the leading and trailing edges of the wing. /68

The problem of area is aggravated during the selection of a wing for airplanes with short flight ranges[35]. On long-range airplanes, the cruising possibilities of practically any wing (whose dimensions are selected from the conditions of takeoff and landing characteristics) are successfully used by means of selecting a flight altitude corresponding to the maximum value for its aerodynamic quality. The fact of the matter is that the effect of specific loading p on the weight characteristics, just as on flight range in airplanes of various classes is not identical. For short-haul, usually two-engine airplanes, it is not great. This is explained by the fact that a change in p in an increasing direction (by means of decreasing wing area) on one hand causes a decrease in takeoff weight ΔG_0 (ΔS), since the weight of the wing is decreased and $c_{y\,cruise}$ is increased advantageously, bringing it close to $c_{y\,max}$. On the other hand, this causes an increase in takeoff weight, since it leads to an increase in relative area of the fuselage cross section (F_f) and the engine cells (F_n); $\frac{F_f + F_n}{S} = \bar{F}$ and the dimensions, and consequently the weight of the power unit (ΔG_{pu}) and the fuel reserve (ΔG_f) are increased. In summary, a situation is possible in which the negative and positive effects of a change in p on takeoff weight are mutually compensated:

$$\Sigma \Delta G_0 = -\Delta G_0(\Delta S) + \Delta G_0(\Delta G_{pu}) + \Delta G_0(\Delta G_f) \sim 0.$$

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[34] See Section 9.4.

[35] With equal takeoff weight, the greater the flight range, the smaller the wing area, since the specific loading on the wing from takeoff weight may be greater in a long-range airplane with the specific loading from landing weight being equal.

A significant increase in wing area and a decrease in p on the same short-haul airplanes which usually have a low cruising altitude may turn out to be harmful, from conditions both of resistance and of weight. True, this will not be to an identical degree under different conditions. For instance, if flight altitude does not exceed 6000 m, then the losses are not great. If it reaches 8000-9000 m, then with an increase in wing area within small limits (by 10-15%), the cruising effectiveness (M_{crk}) may even increase, since the quality (with the same M_{cr}) will increase by 3-4% due to a decrease in relative cross section. However, a corresponding decrease in fuel reserve (with L = const) will not compensate the increase in weight of the empty fitted airplane (G_{ef}). The latter is caused not only by the increase in wing area and the increased empennage area connected with it, but also by the heavier fuselage as the result of increasing the dimensions of the empennage and loads. Therefore, the selection of a wing for two-engines airplanes actually takes on a special acuteness: superfluous area, just as extra weight, is harmful and too little of it can lead to no less /69
mournful results -- the airplane will either have no potential for development of modifications or (in case of the calculation error in determining G_{ef} or k), be unsuited for operation from a certain class of airports. This indicates that selection of the wing must be conducted on the basis of exacting and all-encompassing research with consideration for the unavoidable increase in weight of the fitted airplane during the planning process[36] and the consequent appearance of modifications and, as a result, an increase in takedff weight.

In cases where the potential for development of a modification is exhausted by takeoff and landing characteristic requirements, it is possible to make use of a recently introduced method for increasing wing area by means of installing unfolding tip panels (Fig. 1.27). During cruise, they are pressed against the wing surface, forming a thickened profile, and at low speed they rotate by 180°. In this way, the hinges of the folding tips are not loaded during high speed flight, which is different from the variable sweep wing. It is asserted that "the payload of a typical two-engine airplane, whose takeoff weight is limited by characteristics corresponding to a single working engine is increased by approximately 50% with the use of folding wingtips" [82].

During the planning of any sort of modification variation and with the creation of some reserves, along with the thrust-to-weight ratio and wing area problems arise questions which are connected with landing gear leg height, fuselage volume and strength characteristics of the airframe. An increase in fuselage length (during the period of modification) within determined limits is also possible without increasing the height of the gear leg -- by means of some decrease in the landing angle. The value of this angle

[36] For more detail see Section 2.2.

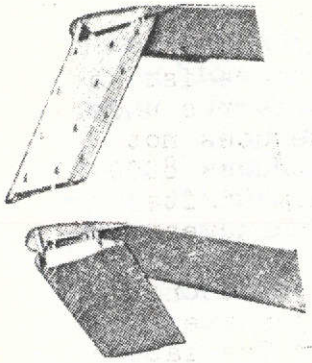

Fig. 1.27. Panel at the moment of position change.

is changed as the result of increasing the length of only the tail portion of the fuselage, and the latter (due to center of gravity conditions) increases by no more than half the total length of the insert (see Fig. 1.26). Consequently, its change is not as great, and in a case where a reserve angle is absent, it can be compensated by a change in wing setting angle.

It is clear, naturally, that reserving volume should not be done. In the wing, such reserves are often formed involuntarily. An increase in fuselage volume will lead either to a decrease in arrangement density or to the creation of an airplane with more seats than is necessary for the basic variation, and if the required passenger seating capacity was determined on a sound base, an increase in the number of seats will decrease the coefficient of passenger loading or the frequency of flights and in the final analysis, it will decrease economic effectiveness. At the same time, a subsequent lengthening of the fuselage (with the appearance of a requirement for increasing the number of seats) during modification of the airplane is not a problem. It is true that there is in this another side of the question: is it possible to prove forecasts in determining the required number of seats (for many years). It is easy to note that the boldest forecasts often prove to be low. The tendency of many designers to somewhat increase the dimensions of the airplane is therefore understandable. This position does not, however, relate to the problem of reserves. /70

Concerning strength characteristics, the advisability of accumulating strenth reserves to exceed calculated loads is dubious. Practice shows that highly effective designs are created with planning for reduced loads [62]. With an increase in takeoff weight in subsequent modifications of the airplane, the natural strength reserves (see Chapter 12.3) which are usually discovered during static testing[37] can be successfully used, regardless of the approach to development of the design. The weight potential is increased to the maximum degree during discovery of wing strength reserves. In the first place this is because strengthening this part of the airplane is more complex than other parts, and primarily, these reserves can be used when it becomes necessary to increase wing area for subsequent modifications. It is true that natural reserves do not always prove to be evenly distributed: they are successfully discovered in some parts of the airplane and not in others. Besides this, in some parts they may be greater and in

[37] For instance, airplane wings commonly sustain 105-110% of the calculated load.

some parts smaller. However, localized strengthening does not as a rule introduce noticeable complications. It should be noticed that strength reserves are not always successfully utilized during modification of an airplane. In the Boeing 737 airplane, as a result of a miscalculation in determining frontal resistance[38], strength reserves were used to increase takeoff weight for the purpose of maintaining the guaranteed flight range. At the same time, there are probably few among the successful airplanes whose productivity could not be successfully increased through natural reserves.

In conclusion, we should speak of two different prerequisites for planning which can be distinguished, arbitrarily of course, since the matter becomes somewhat more complex. In the first of these, the aim of planning is the achievement of the maximum effectiveness of the initial variation, and consequently, the selection of all dimensions in strict accordance with a set productivity and BFL class by means of optimizing the basic parameters, for instance, according to minimum cost of movements. In this, the unavoidable increase in weight characteristics during the planning process, whose regularities are reviewed in Chapter 2.3, should be considered. In this case, development is possible due to natural (unplanned) reserves or along the line of extensive modifications. In the second case, there is a tendency toward reserving for future development of the airplane with minimum trade-offs. The latter may at first glance prove to be a contradiction to the basic rule of planning the optimum airplane, which consists of achievement of a minimum weight with a set productivity ($G_{cp}L$), the minimum cost for the airplane and minimum operating costs. This is indisputably justified. One should only review the technical and economic characteristics of not one airplane in its initial variation, but the profitability of the fleet of airplanes during the course of an extended period of operation with consideration for modifications. /71

Airplanes which are adaptable for modifications, the Il-62 and Tu-154, can serve as illustrations of the aforestated. The first possess development potential with an increase in flight range, passenger seating capacity and load capacity. The characteristics of its first modification the Il-62M [23] testify to this. The dimensions of the Tu-154 airplane, which were determined by orientation on an existing engine (the practice is disputed but also widely used abroad), led in the first place to creation of a heavier airplane than was its predecessor in this class which, generally speaking, corresponds to regularities of passenger airplane development and, in the second place, to creation of definite reserves for the development of modifications [19, 35] which is also progressive.

4.5. Methods of investigation. At the present time, the work of designers and planners of machines and system is conducted

[38] Flight, 9.II.1967.

with consideration for extremely high and varied requirements of a technical character. Together with this, during recent years economic and organizational factors have to an ever increasing degree had an influence on the acceptance of solutions. Therefore, the economic bases of new equipment have become the most important composite part of the process of its creation.

It is understandable that for optimization of complex planning problems in modern passenger airplanes, the methods of parametric analysis, which allow judgment to be made only of separate types of effectiveness (for instance, weight), are insufficient. The area of using separate criteria for evaluation of the different properties of an airplane and the degree of its correspondence to its /72
purpose is even more limited. Cost indices expand the area of usage and create a fuller impression, but are also insufficient for this purpose.

Methods of researching economic effectiveness which are used during the planning process often limit the comparative evaluation of cost of movements (ton-kilometer or passenger-kilometer) of planned and operating airplanes. With this, either the full cost (a') or direct operating expenses (DOE) are determined. Without reviewing the distinctions of these methods, it should be noted that computation is usually conducted for a single airplane on the basis of the averaged statistical values of various economic parameters combined for each actual moment, and the cost of experimental and design development and series airplanes is expressed in these cases with a number of coefficients.

During optimization on the basis of the economic criterion, it is recommended that not one single airplane, but the entire fleet and even the transport system as s whole be reviewed. Besides this, it is advantageous to consider the dynamics of change in the economic parameters of production and operation, such as the cost of an airplane and engines and their repair, the annual output of airplanes, the change in the fleet and annual flight and so forth. Also, in evaluation of advisability for minor and extensive modifications, trade-offs connected with restructuring of production during introduction of modified airplanes must be considered.

The method for dynamic modelling developed by A. V. Glichev satisfies to the maximum degree all these additional conditions which are necessary for the analysis of technical systems. This method considers changes in a number of economic parameters during the process of the entire period of their operation and furnishes thepossibility for evaluating effectiveness of various technical solutions on the scale of the national economy. The possiblity for using electronic computer equipment for solving problems with this method allows significant expansion of the area of research, creation of models of various situations and finding optimum solutions. Besides this, this method is distinguished by a complex approach to determination of economic effectiveness, i.e conditions necessary

for development of new machines (with consideration for planning of modifications) and especially machine systems.

PART 2. PROBLEMS OF AIRBUSES /73

Chapter 5. Appearance and Development of the Idea

5.1. The necessity and the possibility for creation of the airbus. The conept of the airbus is not new, and it was encountered in Russian literature as early as 1911 in the work of B. N. Yur'ev (subsequently an academician). He wrote, "at the present time, the question arises of very high-load aeroplanes, capable of lifting a large number of passengers, so-called airbuses"[1].

Understandably, the impression of airbuses of that time does not fully correspond with modern ones. Appearing again at the beginning of the 1960's, it was researched for 10 years, and the planning and creation of the new type of airplane also underwent changes.

The development of passenger airplanes of all classes is accompanied by a constant increase in their passenger seating capacity. For future development, however, a simple increase in the number of seats became insufficient. New solutions were required which would allow a corresponding growth in the number of movements and an increase in the passenger flow density with organization of the transport system as a whole. In connection with this, the idea of movement organization according to airbus type or the idea of the airbus began to be developed.

Another reason for the appearance of this idea was the striving to eliminate the disparity between flight time and that which is wasted by passengers before and after the flight (obtaining tickets, travelling to the airport, checking and picking up baggage and so forth). The fact of the matter is that the systematic increase in speed noticeably reduced flight time, but reduced the total time spent by air passengers on the road "from home to home" only significantly.

And, finally, the third (but not the least reason in value is the striving toward increasing economy. The methods of solving this problem are various. One of them is reducing the number of types in the airplane fleet. Conditions of development of jet aviation led to the formation of four classes of main-line airplane (short-haul, medium-haul, long-haul and intercontinental). Besides /74 this, airplanes with a minimum of two generations are in operation, which increases the number of airplane types and correspondingly increases the initial cost of the airplane-motor fleet and the cost of its operation. Therefore, with the development of airbuses, the tendency toward creation of an airplane with a wide spread in range appeared.

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[1] B. Ye. Yur'ev, Avtomobil' i vozdukhoplavanie, Nos. 10 and 11, 1911.

Solution of the problem of reducing total time to the minimum is possible by both airplane and airport means. Thus, for rapid movement of passengers, two longitudinal aisles, noticeably enlarged in dimensions are provided in the cabin layout. The number of cross aisles is also increased, as well as the number of doors and their dimensions. Two passengers, walking side-by-side can enter through them at the same time. Ground servicing components are designed for precise servicing of passengers and acceleration of loading and unloading operations. This will simultaneously lead to a decrease in the standing time of airplanes on the ground[2], which will have an effect on the economy of communications which is no less (especially on short routes) than cruising speed. The airport means include, for instance, an automatic ticket installation. In one of the plans, a connection between this machine and a turnstile is provided for the purpose of automatically determining the weigth of baggage, the number of passengers and distribution of seating places for determining the center of gravity. (The latter, like weight, is monitored with onboard automatic systems.) Questions of equipping air drums with underground pipe systems for fuel water and sewage are being reviewed. Means for speeding up delivery of passengers to the place where the airplane is parked and other improvements are being developed.

Work on a further reduction of the total time spent by passengers on the way "from home to home" is progressing along the line of developing low-noise short takeoff and landing airplanes which will in noise level be suitable for operation from urban areas.

Methods allowing solution of the problem of increasing economy and reducing cost of communications include: increasing passenger seating capacity and cargo compartment volume, increasing the commerical weight allotment[3] and reducing specific fuel consumption, decreasing the number of crew members and the number of stewardesses and so forth. The latter is also essential, in that the payroll for the flight crew is one of the main articles in direct operating /75
expenses. A reduction or elimination of the galley compartments or closets will lead to fuller usage of the fuselage volume. The attempt to make operation of the airplane less expensive through

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[2] An increase in turn-around by means of decreasing standing time by, for instance, 200% will lead to a decrease in the airplane fleet by approximately 50%. Besides this, the gap between "spiritual" and physical aging of the equipment will be reduced similarly.

[3] An increase in this allotment (i.e. the relative weight of the commercial payload) will occur in airbuses with the drop in total weight allotment (which is a combination of the commercial allotment and weight allotment for fuel). It is appropriate to recall that the commercial allotment has a greater effect on economy than the weight allotment for fuel (even in a case where an increase in the latter will lead to an increase in range).

increasing its dimensions is in agreement with the advisability for decreasing the frequency of flights due to overloading of airports. The time and fuel losses connected with holding in the air can be successfully decreased or eliminated and therefore the navigation reserve can be decreased (through the "reserve for holding"), which, together with economy of fuel means will lead to an increase in the commercial weight allotment. It is thought that as a result, the economy of the airbus will be greater than that of modern airplanes by 10-20%.

The possibility for rapidly converting into the cargo-passenger and cargo variations with cargoes located in the cabin on pallets in containers is provided in the airplane's construction and layout for the fullest usage of its load capacity for the purpose of increasing economy. The achievement of this purpose is sometimes hindered by the necessity to solve such problems as, for instance, operation from the relatively short airports which small settlements have available. These conditions present definite requirements for the power-to-weight ratio and wing area of the airplane and lead to economic losses.

Regularity of traffic -- one of the factors of existence in any transport system -- acquires exclusive meaning in the organization of traffic according to airbuses (without preliminary sale of tickets). Regularity connected with flights at weather minimums with zero visibility at altitude is provided by equipping airplanes with a system of automatic approach to a landing to the touchdown point.

The modern impression of airbuses leads to the following definition of the concept: an airbus is a short-to-medium-haul airplane possessing a large passenger seating capacity, high economy and high comfort, which provides (together with ground facilities) the maximum shortening of preflight and postflight time and responds to requirements for the new organizational traffic on air lines. The organization of traffic with airbuses is distinguished by its increased flight safety and regularity of traffic. From a purely technical standpoint, the airbus is a high-tonnage wide-fuselage airplane with a large commercial allotment and a short flight range.

This definition may cause an objection, for instance, in relationship to the connection between the concept of the "airbus likeness" of an airplane and its dimensions, passenger seating capacity and range, even more because the concept is also connected with cabin layout arrangement and with movement organization conditions. At the present time, however, all the aforestated is actually connected with this concept.

Jumping somewhat ahead, we say that the evoluation of European /76 and American projects has lead to a rejection of solutions in many initially studied problems in airbus planning. And now it is difficult to foresee whether the name "airbus" and the impression of

it which was compiled during the period in which this idea was developed will be maintained. But the matter is, naturally, not in the name. The new and major factor is that it bears with it third generation airplanes which comprise a quantitative jump (both in dimensions with a comparable flight range and in volume of movements), leading to a new qualitative content. In accordance with this, the problems reviewed below concerning the number of engines, fuselage configuration and increased economy are connected not so much with the concept of an airbus as with the further development of airplanes in general.

Thus, an increase in air movements caused the necessity for developing a new traffic system, and as the result of development in airplanes and especially engines, the possibility arose for creating aircraft which are sharply increased in dimensions. While achievements of recent years -- improved aerodynamic properties, easier and improved design and improved basic engine characteristics -- allowed flight range to be essentially increased with modification of operating equipment, the latest leap in engine building has allowed the development of airbuses to begin. More precisely speaking, the appearance of high thrust engines with a significantly decreased specific weight and fuel consumption (by approximately 25%) has opened the era not only of airbuses but also of wide-fuselage airplanes of all classes. Consequently, the practical necessity for high-tonnage airplanes corresponds well with the technical possibility for their creation.

Understandably, not all planned short-haul airplanes will be included among the wide-fuselage ones. Airplanes which are not so large are being developed for lines on which a significant growth in the passenger flow is not foreseen. These first of all include the Dasso "Mercury" airplane, carrying 143-155 passengers.

The largest leap in changing the dimensions of an airplane, of those observed during the development period of passenger aviation, will apparently also lead to an unusual leap in demand for airplanes of this type. The number of orders received and forecasts have allowed American specialists to assert that the requirements for these airplanes for the world market will be no less than 1100-1500 in 1980. If we recall that the entire airplane fleet of the 116 ICAO countries consisted of 7000 units (including 2700 piston airplanes) up to 1968, these forecasts may prove to be optimistic.

In conclusion, we note that in this part of the book the problems of selection of the number of engines, fuselage configuration and, primarily, the method of moving baggage, i.e. the most disputed ones, are reviewed. The problems of weight effectiveness /77
in airbuses and placement of engines on the tail on these airplanes are reviewed in the third and fourth parts of the book (Chapters 9 and 16).

5.2. Creation of new types of airplanes in the past were never preceded by such lengthy development of projects and such extended discussion, and the problems evaluated did not have such a disputed character as has been the case during the period of development of airbuses. The problems of passenger seating capacity and flight range, number and arrangement of engines, dimensions and shape of fuselages, installation of baggage compartments and organization of acceptance and dispensing of baggage have all been disputed. Therefore, some facts from the history of development in European and American airbus projects are interesting. Their development has occupied a large number of firms in various countries. Controversies in the press and at international conferences of representatives of the planning firms and operating companies have gone on simultaneously. We recall that one of the first airbus projects, bearing the name "Galion" by the French Sud Aviacion firm appeared at the beginning of the 1960's, and the mass operation of airbuses will begin somewhere in the middle of the 1970's. This once again asserts the fact that a great reach exists between the appearance of a new technical idea and the creation of a practical system. Meanwhile this time the research began with the clarification in an especially wide scale on the relationship between the possibilities of new equipment and requirements of the lines.

Determination of the required flight range and corresponding dimensions of the airplane have an essential meaning. As the result of research, the conclusion was reached that within the confines of Europe, the required flight range does not exceed 1800-2000 km. The range of the A-300 airbus (Fig. 2.1), which was at first being developed by France, FRG and England together (the latter later dropped out, but after that Holland joined) corresponded directly to this amount on flights with the maximum number of passengers in the initial project. With this, the airplane was also calculated for a range on the order of 3100-3200 km with a lower number of passengers than was considered and a potential market on other continents. The controversy was essentially not so much over selection of range as much as on the advisable number of passengers, and in the beginning it turned out that the number 200-250 was the limit. However, the A-300 airbus was calculated for 300 passenger seats. The maximum number of passengers was determined by airport conditions in such a way that on short lines (i.e. up to 1800 km) the airplane must be operated from comparatively small airports, and on routes of greater length, the takeoff and landing characteristics are not limiting factors.

The configuration of the airplane was changed many times during /78 the process of project development. Some firms, following a tendency which predominated earlier, provided a layout with engine installation on the tail. In the project for the A-300 airplane, despite the very large diameter of the engines, they were located beneath the wings (see Fig. 2.1) and in the project of the BAC.3-11 (England), they were located on the fuselage. The question on the advantages of one engine placement or the other remains disputed,

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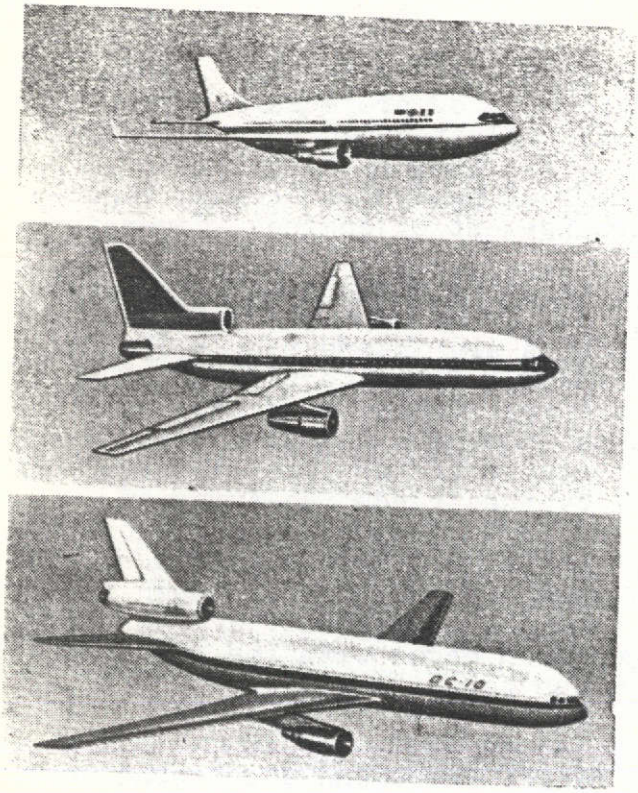

Fig. 2.1. A-300, L-1011 and DC-10 airbuses.

and it is analyzed in Chapters 14 and 15. The question on the number of engines has proven to be no less disputed. Some have proven the advisability of three engines, and others -- two. The proponents of two engines at first considered that the economy of the airbus with this would be higher by 12-13%, and then they specified more accurately: by 8%. At the end of the discussion, the difference in evalution boiled down to an insignificantly small amount. The latter is explained by the increase in calculated cost of engines with the increase in their dimensions /79 (as opposed to the decrease initially expected)[4].

The configuration of the fuselage was also varied. A circular shape with a single deck layout was finally selected for its cross section. Earlier, a horizontal form, and in other projects a vertical double bulb (with a double deck layout) were looked at. The dimensions of the cross section (the height of the cabin above the floor and the height of the cargo compartment) in the A-300 airbus will be almost the same as in the giant Boeing 747. This similarity is convenient in operation in that it allows the same baggage containers to be used. The tail layout of the A-300 does not repeat that of second generation airplanes, but has a low horizontal stabilizer placement. A T-shaped tail empennage, which is similar in properties to airplanes with engines mounted on the tail (see Chapter 16) is provided in the project for the BAC.3-11[5]. The angle of wing sweep was also, naturally, researched. Preference at first produced a value of 20-25°, at which operational expenses were approximately 1.5-2% less on short flights than with an angle of 30°. In the project of the A-300, it was left at a value close to the latter (28°), allowing cruising at somewhat higher speeds,

[4] For more detail see Chapter 7.

[5] The development of its project was rather far along, but construction was halted due to failure of the government in financing.

which is economically effective at a distance on the order of 300 km.

The question on the necessity of a galley was also disputed. With this number of passengers, it occupies a large part of the usable volume and significantly increases the airplane's weight. The necessity for having a food supply weighing 0.9-1.1 kg per passenger and the same quantity of liquid (in accordance with service standards on international routes) leads to a weight increase in the construction and equipment of 10.6 kg for each passenger.

The constant change in passenger seating capacity and overall dimensions (tonnage) in projects for the European airbus is an example of the extended searches and indetermination of forecasts. Thus, the number of passengers in the "Galion" project was intended to be 270, in other project, the HB-100, it was intended to be within limits of 260-225-200. The project of the A-300 and A-300V airbuses had the same tendencies for reviewing the number of seats (300-265-252-290) and takeoff weight at 120-140-150-125-134 t. Some irregularity in the latter two numbers in these series is explained by the simultaneous changing of flight range. Fuselage diameter also changed according to the number of seats from 6.4 to 5.9, and then to 5.5 m, and wing area changed within limits of 286-255 m^2. Engine thrust was also changed. Location of the engines on the airplane was also a big dispute, but in all stages of the project's development, the power unit was placed beneath the wing.

The projects for American airbuses were developed with an increase in load capacity and flight range, and consequently in the dimensions of the airplane (both are characteristic for the transport systems of two continents). Furthermore, the changes did not only touch on dimensions. Study of the many problems of the airbus led to their negation in those American projects, and it was there that the question arose as to whether or not these airplanes as a whole should be called airbuses. /80

In the beginning, the basic tendencies in the development of the American projects should be looked at. Investigations here into the problems of the airbus led to different solutions than in Europe, primarily in relationship to flight range. The fact of the matter is that in the USA, the number of fully filled routes with a radius of 4000-4200 km is approximately equal to the number of similarly filled short routes, and in Europe the latter predominate. The large volume of movements led also to a large passenger seating capacity in the DC-10 and Lockheed L-1011 American airbuses (see Fig. 2.1). It is located within limits of 340-350. Another of the basic tendencies consists of the striving to create an airplane with a wide spread of medium ranges and toward development of modifications of the international class with a potential for range

increase. It is easy to see in this a tendency toward reducing the number of types in the fleet. The economic effect in this case is evident. A three-engine layout (two engines located beneath the wing, and the third on the tail) was selected for the DC-10 and Lockheed L-1011 airbuses. The selection of this number of engines was affected not only by the economic advisability of the layout (see Chapter 7), but also the presence at that time of engines developed during the competition for the C-5A and also a striving toward unification, which consisted of using the same engines on short-haul (in quantities of two), medium-haul (three) and intercontinental (four) airplanes.

Wing sweep in the American airbuses comprised $\chi = 35°$, which for the selected length of the flight is optimal. During planning, both low and middle placement of the wing were reviewed to reduce landing gear height, which is selected with consideration for possible lengthening of the fuselage in the future. The designers, as with the A-300, moved away from the T-shaped tail empennage, even with the three-engine layout (see Chapter 16) selected a circle for the cross section of the fuselage and did not use a double decked layout.

This is a short abstract of the history of creation of European and American airbuses. It shows that during project development they were limited by the solution of problems which were primarily connected with the creation of a multiseat airplane for massive passenger movements and reduction of preflight and postflight time. Other problems, which significantly expand the possibilities of the airbus, but whose solution has still not progressed to the required degree, were excluded by the designers so as not to extend the periods of development. These problems include, for instance, /81 questions of flow laminarization, control of the boundary layer, the problem of shortened takeoffs and landings, problems of external noise and so forth. (The latter, by the way, must be solved with consideration for the fact that airports must be located near centers of population for the purpose of shortening "ground time.") The solution of these and other problems in the future will transform the airbus into transportation with exclusively great possibilities.

Chapter 6. Problems of Transporting Baggage on Airbuses

Of all the problems arising during the planning of airbuses, the most disputed one was perhaps that problem, since it is included among those problems which define the very "philosophy" of the airbus. During its study, the idea of "keeping baggage," i.e. transporting it similarly to railway movements, arose. A large number of variations were studied on the basis of the three major conditions for solving the problem: comfort, weight and economy. During this, all the possible "pros" and "cons" were reviewed. The discussions were often limited to logical arguments, although solution also allows analytical evaluation.

In reality, the problem is complex. On one hand, the organization of checking and picking up the baggage of 300-500 passengers in a minimally short time requires significant means for creation of ground facilities, and on the other, the "kept baggage" system is tied to a decrease in the airplane's efficiency. Consequently, a combined solution of the problem which balances ground and onboard losses is required. Meanwhile, the greatest share of the losses must be sustained at airports, inasmuch as in any case they will be subjected to reconstruction which is connected with a significant increase in the flow of passengers and a requirement for automation of many ground service processes, beginning with sale of tickets and ending with retrieval of baggage.

The problem of creating new air transport means, airbuses and giant airplanes, has become, therefore, not only an "air" problem but also a "ground" problem.

The handling of baggage (sorting it according to flight) at airports occupies a multitude of workers, and the area allocated for this purpose occupies a large area. Thus, at Orly airport (Paris) the hall occupies an entire hectare, and in Los Angeles the total area of the six buildings is 2850 m^2. Eleven thousand pieces of baggage are handled here per hour. In 1975, this number will increase to 19,500, and in 1980 it will increase up to 32,500. All this is easier to imagine if we recall that at such large airports, a takeoff and landing of an airplane with a passenger seating capacity on the average of 120-140 persons occurs every 1-2 min. Orly airport, which was constructed in 1961 and calculated for 6 million passengers per year, has already become insufficient -- /82 it is being expanded up to a through-put of 9 million per year.

Automatic devices for handling baggage are not yet being used, and with manual sorting, many mistakes get by which, for instance, in the USA lead to an annual shipment of up to 300,000 suitcases to the wrong destination. "Aviation Week" (August 17, 1970) communicates some interesting facts. At the central point for unclaimed baggage owners' inquiry, a whole ocean is accumulated. It is sent here from various airports of all lines after fruitless inquiries for a period of 72 h. During further inquiries using computer equipment, only 30-35% of the suitcases find their owners. After 4 months of storage, an average of 200 suitcases are sold at auction monthly. This has given birth to a joke: "Breakfast in Paris, lunch in New York, baggage in Beirut" and promoted the appearance of the "kept baggage" idea.

It is appropriate to recall that during the development period of massive air transport, the organization of passengers' journeys without baggage, i.e. with it being checked beforehand, was considered progressive. The passenger was spared from worrying about it and from the role of a porter. As airplane dimensions and passenger seating capacity increased, the time for delivering baggage began to increase, and on short flights it became comparable

with the flight time. The matter is also aggravated by the fact that loading and placing many tons of cargo along the large but narrow cargo compartments is done entirely by hand. This heavy and incomparably time-consuming labor contradicts the very impression of a modern liner, which is filled with automatics, electronics and radio navigation equipment. Therefore, the problem of mechanized loading and unloading operations on the basis of containerized cargoes arose in its time. However, it did not immediately receive a practical solution. The reason for this is a significant weight increase on the airplane and a requirement for ground facilities. The weight of the removable containers alone comprises 2.8-3% of the maximum commercial payload weight, and considering the non-removable elements of mechanization, it reaches 4.5-6.0%, and this is significant.

For wide-fuselage airplanes and the airbus traffic system, the question of accelerating the checking and picking up of baggage acquired special sharpness. Its transportation together with the passengers, which is accepted on other forms of transportation, also gave birth to the "kept baggage" tendency. Strictly speaking, this concept does not have a definite interpretation in its usage in air communications. It is usually understood to mean that the passengers do not check the baggage, but place it onboard the airplane, sit it in a separate area and collect it upon arrival. We note that "keeping baggage" in a literal sense, i.e placing it near the seat as in a railroad car, is impossible to realize on an airplane. This solution would hinder the requirements of general arrangement, minimum weight of the construction, safety (during /83
evacuation) and others. By the concept "keeping baggage until boarding," we take to mean its placement on racks by the passengers themselves. In this we can differentiate between two types of racks: stationary ones with a device for approaches to it inside the airplane and movable ones with external loading (Fig. 2.2a).

This system is contrasted to containerization of baggage and cargoes. The "keeping baggage up to the container" system (Fig. 2.2b), which also excludes preliminary baggage checking, is an obvious compromise. In this case, the passengers themselves place it in the containers, which up to their loading on the airplane are located on specially equipped places on the airport which are placed along the lines of movement of the passenger flow toward the landing point (Fig. 2.2b). Upon arrival of the airplane, the baggage is set in places which are also accessible for passengers. The containers are made standardized and suitable for all airplanes with large fuselages. Their dimensions and shape are determined by conditions of the effective usage of spaces in the lower cargo /84
compartments. This system combines the advantages of the two preceding ones and the deficiencies belonging to them are eliminated. Only operational complications during flights with intermediate landings can arise, but these can be eliminated.

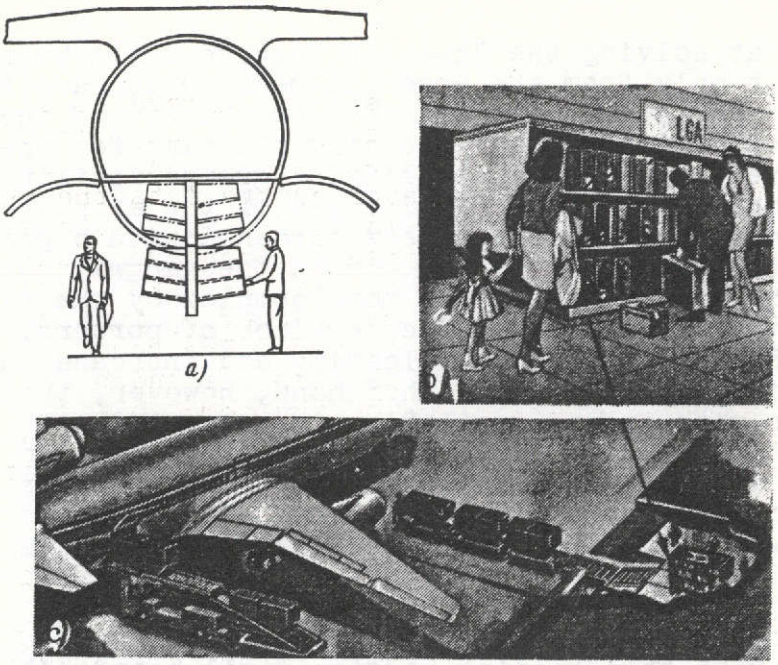

Fig. 2.2. Ways of loading baggage into an airplane: a. external loading of baggage on racks; b. "keeping baggage up to a container;" c. loading containers into the airplane.

In the weight relationship, the airplane fuselage with loading by "keeping baggage until boarding" turns out to be 2.5-3% heavier due to the long length and lowered degree of space usage (or by 0.5-0.6% of the weight of the fitted airplane). This is justified under conditions of an equal number of passengers. With equal length of the fuselages (of two compared variations), its weight together with the containers turns out to be 4-6% higher with container loading (or 0.8-1.2% of the weight of the fitted airplane). However, with this, the number of passengers can successfully be increased by 5-6%, and the usable volume of the cargo compartment can be increased by 30-40%.

Attempts at solving the "keeping baggage until boarding" abroad were limited to, perhaps, the French projects of the 270-seat "Galion" and the 250-seat Nord-600 airbuses, whose development has long since ceased. Later, lowering platforms were proposed, which would allow passengers to stow and retrieve baggage. In other variations, racks located either in the center portion of the cabin (with the fuselage section which would be pulled out along its horizontal axis, for instance, according to the layout of A. A. Badyagin) or in the subfloor section, were proposed.

Attempts at solving the "keeping baggage until boarding" problem emanate not only from the economic means necessary for creation of the ground facilities, but also follow the aim of increasing convenience for passengers and reducing the time for checking and retrieval of baggage. While simplifying ground facilities at the expense of decreasing the effectiveness of the airplane is disputed, the convenience of passengers burdened with baggage during their movement around the airport and on the gangway is highly doubtful. (The situation is made more complex by the fact that some passengers avail themselves of the services of porters, which could noticeably decrease the tempo of loading and increase the standing time of the airplane.) On the other hand, however, the achievement of these goals with ground facilities is connected with capital re-equipment of airports. In other words, the question boils down to whether it is preferable to make capital investments in the reconstruction of airports, come to terms with a decrease in airplane effectiveness under certain conditions, or find a compromise solution.

We will review the reasons for a decrease in the effectiveness of the airbus with the "keeping baggage until boarding" system.

One of the distinguishing peculiarities in airbuses is connected with the character of using the fuselage volume, or to be more precise, with the tendency for decreasing the degree of its usage. This takes place as a result of two reasons. In the first place, the relative size of the cabin space belonging to one passenger is increased (from 0.8-0.95 up to 1.2-.13 m^3 per passenger), which is in connection with the presence of two aisles and a general inclination toward increasing comfort, in particular toward more spacious arrangement of seats and an increase in their dimensions (for more detail see Section 3.5). In the second place, the questions of utilizing the load capacity of the airplane (on flights with an underfill of passengers) is solved anew. The fact of the matter is that the maximum commercial payload of airplanes of the first two generations having fuselage diameters up to 4 m is determined by conditions of space, i.e. the maximum number of passengers and with this full loading of the baggage compartments. In other words, the dimensions of the fuselage and its strength are determined from these conditions. This problem is solved in another way on airbuses. With the maximum commercial payload, the baggage compartments are not fully loaded. The degree of their usage increases with a decrease in passenger loading, which is convenient since the usable volume of the fuel compartments can be increased (with an increase in flight range) with the decrease in commercial payload from conditions of takeoff weight. Loading of all baggage compartments of an airbus with a full number of passengers would lead to an increase in the maximum commercial payload by 30 to 40% above the required or assigned weight. Another index which characterizes this peculiarity in wide-fuselage airplanes is the value for the relative volume of the baggage compartments. While in airplanes having fuselages with a diameter less than 4 m, the volume of

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the baggage compartments beneath the deck and belonging to one passenger comprises 0.2-0.24 m^3, with a fuselage diameter equal to 5.5-6 m, it reaches 0.38 m^3. We recall that the volume necessary for transporting only the baggage of a single passenger is equal to 0.17 m^3 (with an average baggage weight of 20 kg and a density of 120 kg/m^3).

Consequently, the advantage of large diameter fuselages is their significant reserves in baggage compartment space, which allows a large cargo to be brought on board during flights with an underfill of passengers. Inasmuch as the average annual coefficient of passenger loading does not exceed 0.65, and the rate for transporting 100 kg of cargo corresponds approximately to the fare for a passenger ticket, the economic effect from transporting cargoes in the reserve spaces is essential.

It is well-known that the rate of increase in cargo shipments significantly exceeds the rate of increase in passenger movements, although in volume the former still lags noticeably. Thus, in 1970, profits from cargo operations on foreign lines were more than five times smaller, although the growth rate allows the assertion to be made that by 1985 cargo movements will bring in revenues greater than passenger ones. Still, forecasts for the volume of the latter in 1980 exceed the 1960 level by 10 times[6] (it is not by chance that air cargo is now being likened to a "sleeping giant"). Such a huge increase in cargo turnover is also one of the reasons for /86
a transfer to wide-dimension fuselages with large spaces for cargo compartments. Another, as is well-known, is the condition for placing a large number of passengers.

The creation of sufficient reserve spaces is also advisable in another sense. The fact of the matter is that one of the characteristic peculiarities in the development of air transport consists of the periodic appearance of gaps between the demand and the supply of the number of seats in the airplane fleet[7]. The maximum degree of this will be reached during the mass introduction of airbuses. Their large cargo compartments, however, will allow the breech formed to be filled with cargo shipments. The fact that airbuses with a maximum seating capacity of 350 seats are being ordered for the first period with an arrangement for 250-270 seats and freer seat location can apparently be explained by this peculiarity. As the passenger flow density increases, seat installation will apparently be brought up to the maximum value. By this means, either the coefficient of passenger loading can be successfully supported at the established level or at least its sharp decline can be prevented. Load capacity in this can be realized by the simultaneous shipment of cargoes.

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[6] In the 116 ICAO countries, Interavia, AAE, No. 8, 1969.
[7] For more detail see Section 3.2 and Fig. 1.15

The selection of a system for transporting baggage has an effect on baggage compartment reserves, which reach their maximum value with containerized loading. With realization of the principle of "keeping baggage until boarding," the amount of loss in space depends on the arrangement and construction of the racks. This is explained not only by the lighter density in baggage placement. The fact of the matter is that large-dimension fuselages have two full-sized decks, the lower of which is a cargo deck. The "kept baggage" system often disrupts its cargo utilization. In order to leave their baggage there, passengers must pass along it and then climb into the cabin along an internal gangway. Gangways and several vestibules or corridors[8], which are significant in size occupy a large part of the space, and a small part remains for cargo containers.

The "keeping baggage until boarding" system will in any form of its realization (i.e. with any arrangement of baggage and passenger compartments) lead to significant losses in space. Their size depends on arrangement of passenger approaches to their baggage. These losses, as well as the lower density in packing the baggage, decrease the coefficient of space usage in the baggage and cargo compartments (by almost half) and consequently also decrease the degree of cargo capacity usage on flights with an underfill of passengers. All this decreases the economic effectiveness of the airplane and is one of the chief obstacles in the way of realization of the "keeping baggage until boarding" idea.

The attempt to explain the hindrance of this idea not with the decrease degree of load capacity usage (with the obstacles cited), but with the rigid airplane requirements for center of gravity and with their sensitivity to where the majority of baggage is placed: in the tail or in the nose portion, is disputed. The same is true of the hope for a possibility of creating a "liberal center of gravity." In reality, baggage also noticeably affects the center of gravity on high-tonnage airbuses (180-220 t), although its weight does not exceed 4% of the takeoff weight of the airplane. However, with the "kept baggage" system, its effect is no greater than with containerized baggage. True, in the first case the freedom of baggage placement necessary in operation is somewhat crowded, since a definite place on the racks is allocated for each row of seats and their loading is connected with placement of passengers. The major factor is that questions of center of gravity have been solved to a known degree by providing a sufficiently wide center of gravity envelope and creation of an on-board automatic weight and centering device (AWC), which allows the loading process to be controlled (this was developed here in 1961-1962.[9] It has been widely used abroad since 1964-1965). /87

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[8] Ye. Aleshin et al., "Kept baggage," Grazhdanskaya aviatsiya, No. 5, 1971, p. 21.

[9] For more detail see p. 196.

It is appropriate, by the way, to note that the AWC, which was extremely useful for airplanes of previous generations has become absolutely necessary for airbuses for the following reasons.

1. Airbuses must have a wide center of gravity envelope. The AWC allows it to be expanded without weight losses by decreasing the usually large reserves of stability. This is possible because the AWC reduces errors in centering due to inaccuracy in airplane loading to zero.

2. The size of this error is significantly increased on airbuses as a result of an increase (by 50%) of the relative weight of the commercial payload. Besides this, its weight is determined on the basis of an average value for the weight of a passenger (75 kg). The total error from averaging increases sharply with an increase in the number of passengers.

3. Elimination of preliminary baggage checking will lead to the elimination of its weighing, and without knowing its total weight it is impossible to determine the takeoff values for weight and centering if there is no AWC on the airplanes.

Consequently, the chief deficiency in the "keeping baggage until boarding" system is the low usage of space and load capacity. This situation is illustrated by a comparative analysis in which the fuselage of a Lockheed L-1011 airbus was used as the prototype. The relationship of spaces and the amount of reserves in one case and the loss in another were found analytically by an approximated calculation. The results, therefore, do not pretend to have high accuracy. In this analysis, the effect of type of baggage transportation on the airplane's load capacity, which was limited by volume (with an underfill of passengers) was studied. In other words, the coefficient of loading (K_ℓ) for the airplane was determined with a change in the coefficient of passenger loading (K_{pl}) for two variations being reviewed (Fig. 2.3). Each of them correspond to the curve $K_\ell = f(K_{pl})$, and the cargo weight of the loaded airplane in the reserve space can be determined from the equation /88

$$G_c = n_{pax\ max}[K_{cp} \cdot K_\ell - (75 + q_{bag}) \cdot K_{pl}],$$

where $K_{cp} = \frac{G_{cp\ max}}{n_{pax\ max}}$; q_{bag} = 15 or 20 kg of baggage per one passenger.

The degree of satisfaction of one of the main requirements for the new type fuselage -- the requirement for flexibility in payload transportation -- is expressed in the relationship of the coefficients K_ℓ and K_{pl}. Flexibility consists of the possibility for increasing cargo shipments when there is a decrease in passenter loading with a minimum of refitting (in particular, without

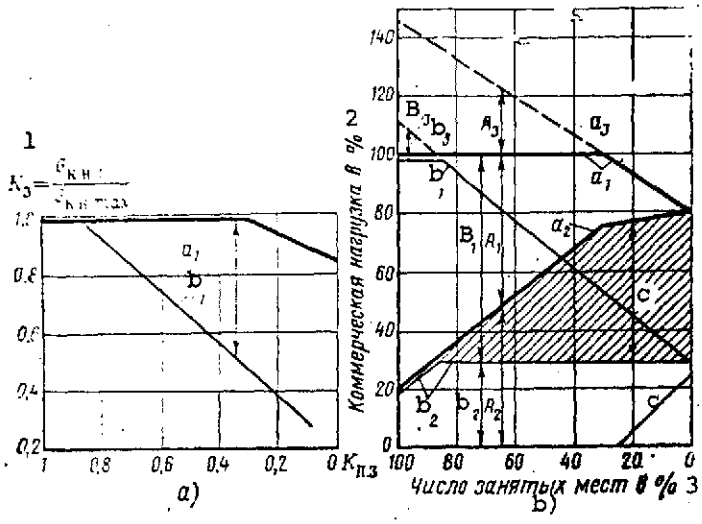

Fig. 2.3. Possible commercial payload in airbuses from conditions of fuselage space usage: a. relationship of coefficients; b. possible cargo shipments with containerization and in the "baggage kept until boarding" case.

Key: 1. $K_\ell = G_{cp\ i}/G_{cp\ max}$; 2. Commercial payload in percent; 3. Number of occupied seats in percent.

removing seats from the cabin[10]), i.e. by means of using reserves. An inclination toward this is connected first of all with the high cost of airbuses and the resulting necessity to increase profitability, and secondly with an intensive increase in cargo flow, which creates the prerequisites for increasing profitability. /89

It is evident from the graph (see Fig. 2.3a) that with containerization of baggage and cargo and with the minimum number of passengers (curve a_1), the possibility for transporting the maximum commercial payload weight can be maintained. With the "kept baggage" system, the value for K_ℓ in our example falls to 0.75, when $K_{pl} = 0.6$ (curve b_1). Profitability of the airplane also changes correspondingly.

The possibility for using fuselage spaces for transporting cargoes with two systems of baggage transportation is also illustrated in Fig. 2.3, b. On the graph, besides the curves describing changes in the maximum commercial payload weight depending on the number of occupied seats (a_1 is containerized loading, b_1 is "kept baggage"), the curves (a_2 amd b_2) of the maximum possible weight of mail and cargo loaded in addition to the baggage are given. The dashed sections of the commercial payload curves (a_3 and b_3) show its possible weight with full usage of all cargo containers (i.e. loading limited by volume, and on the horizontal sections a_1 and b_1 it is limited by weight, i.e. stability of the airplane). The composite weight of the load is shown with arrows: A_1 is the weight of the passengers with baggage and A_2 is the weight of the cargo.

[10] Usage of the cabin with removal of the seats will lead to: a significant increase in the airplane's weight (cargo door, reinforced floor), an increase in standing time and the appearance of problems in storage and distribution of a large number of removed seats (stack-up in some places and shortage at others).

Arrow A_3 shows the amount of cargo loading reserves (according to container space), which is used during a flight with an underfill of passengers. Arrows B_1, B_2 and B_3 are the same, but for the loading variation according to the "kept baggage" principle. Arrow C and the striped zone show the possible increase in cargo weight with containerized loading. Curve c expresses the amount of the load (the number of passengers and the weight of the cargo), corresponding to the threshold of profitability, which is equal for the two reviewed variations. Both charts graphically show the greater transport possibilities of the airplanes with containerization of the cargoes.

The above can also explain the fact that the problem of "keeping baggage until boarding" has not been solved from an arrangement or from an economic point of view on foreign airbuses. At the same time, the high passenger seating capacity and load capacity required a new approach to the problem of loading and unloading operations and to shortening the time for accepting and dispensing baggage. A solution was adopted which predetermined the further course of development, and which progressed along the way of creating automatic systems for containerized shipment of baggage and cargoes. High requirements were defined for these systems: duration of loading and unloading operations must not exceed 3-5 min (standing time of the airplane depends on it); as well as speed in returning baggage to passengers, reliability of the work, its compatability with existing systems, etc.

One of the best known systems for handling baggage, developed /90 in the USA in 1966 ("Telecar"), is based on the use of electronic computer equipment. The system includes: a multi-branched railway and a large number of carts with linear motors (each carrying two-three items of baggage weighing 40-50 kg), equipped with "memory tracking" blocks and moving at a speed of nearly 25 km/h. Stationary counting stations use data written on control tags which are fastened to the baggage and guide the carts to their destinations. The passenger, arriving at the airport to board an airplane, sets his baggage on the cart and places the control tag in the corresponding clamp. After this, the cart automatically delivers the baggage to a point, where it is loaded on the airplane. The passenger, arriving at his destination airport, inserts the control tag in the counting device at a baggage dispensing point convenient for him, and the baggage is delivered to this point on a cart. The baggage handling process is in this way almost totally automated. The through-put capacity of this system is 1800 carts per hour with a minimum of manual operations.

Rejection of preliminary checking of suitcases (all evil, in the final analysis, is included in this) and automatic control of the system of containerized baggage and cargoes will aid, obviously, in coping with the "approaching avalanche" of passenger baggage, which is inevitable with the massive usage of wide-fuselage airplanes.

It is interesting to note that for transporting passengers from the air terminal to the airplane (and back upon arrival), self-propelled coaches (holding 150 passengers) which are raised up to the level of the airplane threshold on their own lifts are being created. After mooring (it is parked at some distance away from the airplane), a "vestibule" up to 3 m long moves out of the coach. The coaches are equipped with an air conditioning and heating system.

In conclusion, some conclusions can be drawn.

With the presence of a sufficient quantity of cargo on air-flights, a container system for transporting baggage is more economical, despite the expenses for creation of the ground equipment. It will lead, as has been shown, to the maximum usage of the new (extremely expensive) aviation equipment.

It is also necessary to agree with the fact that in the planning of airbuses for air routes at which there is not a cargo flow (or it is insufficient), the "keeping baggage until boarding" system may prove to be advisable.

The best compromise in the solution of the two conflicting problems of transporting and handling baggage, which is to say the problem of "air" and "ground," is apparently the creation of a "transfer or combined system for transporting baggage and cargo. /91 With this system, it is possible to keep the baggage and containerize the cargoes for transportation, and as the "ground" is rebuilt, to gradually transfer to full containerization of baggage and cargoes. The advisability of this solution is explained by the fact that the second of the composite parts in the total air transport system complex -- airports with their ground services -- will be reconstructed as the airbus fleet is developed. In other words, overcoming the "ground barrier" problems, as have been shown, is extremely complex and will apparently be done gradually.

Chapter 7. The Problem in Selection of the Number of Engines and Fuselage Dimensions

7.1. On the history of the problem. The problem of selecting the number of engines, which proved to be relatively complex during the creation of airbuses, did not arise for the first time but has a common factor. While fuselage dimensions are connected with the required number of seats and, consequently, forecasts on the growth in movements for the transport system as a whole, selection of the number of engines is included among the problems which are solved by means of researching an actual airplane type.

The four-engine layout was born and supported during the period of piston aviation, when insurmountable obstacles appeared preventing a further increase in engine power. And chiefly, this

layout, even up to recent times remained ideal in relationship to providing flight safety with minimum economic expenditures. The three-engine presently used was prompted by the appearance of engine mounting on the tail and an increase in their reliability. The major role was, however, played by the circumstance that the weight and economic characteristics of airplanes with three and four engines, projected with equal degrees of safety (with the failure of one of the engines) and equal productivity are close together. The three-engine layout, but with a different engine arrangement than in second generation passenger airplanes (in which all three engines are located on the tail), and namely: with two engines located beneath the wings and one on the tail, first appeared on the Tu-14 torpedo carrier in 1947 [20]. Now it has become reborn on American airbuses. It is appropriate to note that during the period of piston aviation, or more precisely at the end of the 1920's, "Fokker" and "Ford" trimotor airplanes appeared. After a 30-year break, the three-engine layout was renewed. True, the third engine was then located in the nose portion of the fuselage. Recently, a layout was proposed for an airplane with asymmetrical placement of the three engines beneath the wing, one beneath the right and two beneath the left (or vice versa) at different distances from the axis of symmetry for the purpose of pairing the yawing moment should one of them fail.

The use of the two-engine layout in the planning of short-haul jet airplanes ("Caravelle," DC-9, Boeing 737, BAC.1-11, Tu-124, Tu-134, and "Mercury") with tonnage approximately doubled (in comparison with two-engine piston ones) did not cause doubt. True, the fleet of such airplanes grew slowly at first, over the course of two-three years, and then grew very rapidly. This is connected with an increase in confidence in this layout, and primarily, with the development of by-pass engines which appeared at that time[11]. They allow the creation of economic airplanes with the necessary degree of safety. When the impression was formed of short-haul third generation airplanes with their passenger seating capacity sharply increased and, as a result, the idea of the airbus was developed, the two-engine layout proved to be extremely disputed and became the object of a huge argument. As the result of extended searches, a power installation with two engines was used for the European airbus and one with three engines was used for the heavier American ones. The appearance of engines with a high degree of by-pass promoted the use of two engines[12] on airplanes weighing 120-150 t and three engines with a weight of 180-200 t. Four of these engines are used only on airplanes weighing 360 t. /92

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[11] The exception was the "Caravelle" airplane, whose initial variation had single flow engines, but all its modifications have double flow ones.

[12] Second generation airplanes weighing 100-160 t have four engines.

It should be noted that the installation of four engines on airplanes having a takeoff weight of 180-200 t may also prove to be economically effective (even with a lower degree of by-pass), if the engines are distinguished by low values for specific engine weight and specific fuel consumption, high indices of life and reliability or optimum combinations of all indices. Such a factor as the degree of an engine's readiness for the beginning of an airplane project development does not play a minor role in engine selection. This in itself determines two halves of the index of its completion. Besides this, the development cost of a modern engine, and then only gradual increases in life and reliability have a noticeable effect on the economics of the airplane. The chief factor is, however, that the development of engines and their finishing occupy more time than the creation of an airplane. There exists, as has been noted, an optimum compromise between effectiveness and time for introduction into operation. With this, the value of higher characteristics in one case, and also low cost in another, are easily determined. The value of an earlier period for introduction into operation requires careful study. It is appropriate to note that for selection of engines for the European and American airbuses, their preliminary development which was accomplished during competition for the C-5A transport airplane had an effect.

Turning to the question of selecting the number of engines for /93 airplanes of various classes, it should be noted that short-haul airplanes were also built along the two-engine layout this time, but they had significantly larger dimensions. The area of expediency in their usage was, consequently, displaced. (This process can also be seen as the tendency toward decreasing the number of engines on airplanes of the same dimensions.) We recall that in the development of piston aviation, an increase in the number of engines went along with an increase in the airplane's tonnage, and then the areas of their optimum number (not only two, but also three and four) periodically shifted in the direction of higher takeoff weights, which is to say larger dimensions of the airplane. Thus, the two-engine configuration during the period of piston and turboprop aviation was rational for airplanes weighing up to 20 t, and during the jet period it is rational for airplanes up to 40-50 t. With engines having a high degree of by-pass, this limit is displaced up to a value of 120-150 t. The rationale of such a significant leap also proved to be doubtful. Concerning the relationship between the number of engines and flight range (i.e. airplane class), there exists a definite limit in range, after which the installation of three engines is better than two, and another limit exists after which four are better than three (with all other conditions being equal). Understandably, these limits are not sharply expressed, but in the majority of cases, they are limited to the values which are accepted in classification (see Table 1.1). As concerns the relationship between the number of engines and weight of the airplane, it is justified (as shown by the aforestated) only for different stages of development in aviation.

The problem of the number of engines is closely tied to the question of the airplane's power-to-weight ratio, which is selected in conjunction with a definite specific wing loading, i.e., which is the result of a solution to the common problem of the engine and wing. The takeoff configuration is usually the condition for selection, but it may also prove to the landing or cruising configuration. In a word, this problem has a concrete character, in which the achievement of high aerodynamic properties in combination with a high lifting force during both takeoff and landing is an important aspect. Changes in flight data upon the failure of one engine requires the best compromise between characteristics of cruising and low speed flight.

Conformities in changes in the power-to-weight ratio during the process of passenger airplane development represent some interest. Thus, the increase in its value in jet airplanes can be noted if the process is looked at only chronologically. This is explained by a characteristic feature in the development of these airplanes, that medium and heavy airplanes were created in the beginning, and short-haul ones after that. For the latter, the two-engine layout and, as a result, a higher power-to-weight ratio is preferred. The creation of highly efficient airplanes along the three- and two-engine layout (with a higher power-to-weight ratio) /94 promoted a decrease in the specific weight of engines (γ_e in Fig. 2.4) and specific fuel consumption (c_R). The power-to-weight ratio can also be increased as a result of increasing the gradient of drop in thrust according to speed by increasing the degree of bypass in the engines.

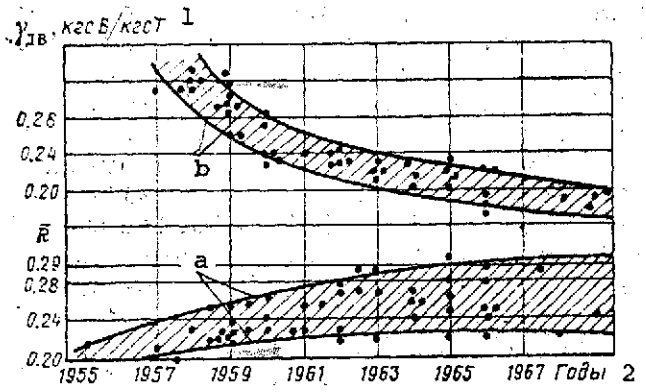

Fig. 2.4. Change in the power-to-weight ratio of airplanes (a) and specific engine weight (b) in the process of their development.

Key: 1. γ_e, kg of weight/kg of thrust; 2. Years

If we look at the development of the airplane within the limits of each class or follow the course of development along the line of modifications, it is possible to note that a conformity in the growth of the power-to-weight ratio in the development of types (or classes) of airplanes is not observed. Is it possible to foresee an increase in power-to-weight ratio in the future? In medium and long range airplanes, there will apparently be no significant increase[13].

[13] If we look at the power-to-weight ratio not as the starting, but as the takeoff one, i.e. with consideration for the drop in thrust according to speed.

It is not determined by conditions of safety on takeoff and would doubtless prevent a further increase in economy. It is sounder to propose that improvement in engines, i.e. a reduction in "the cost of thrust" will be used to increase airplane economy. In short-haul airplanes, on the contrary, a leap is occurring the growth of the power-to-weight ratio, whose explanation should be sought in the definite tendencies of development in this class. These first of all include a sharp increase in passenger seating capacity (from 70-80 up to 250-300 passengers) and the use of the two-engine layout on airplanes weighing 120-140 t.

When looking at the problem of power-to-weight ratio ($\bar{R}$), the question naturally arises -- in what limits is the growth in its value compensated by an increase in technical perfection of the engines with the takeoff weight (G_0) maintained unchanged? In a case where the number of engines is not changed, the weight and economic effectiveness is maintained in full measure only under the conditions $\bar{R} \cdot \gamma_e = \text{const}$. If not only the specific weight of the engines (γ_e), but also the specific fuel consumption (c_R) are changed, then the following equation can be presented to solve this problem: /95

$$G_0 = \frac{G_{cp} + G_{af} + G_{eq} + G_{fit}}{1 - (2.19 - 3.54\gamma_e) \cdot \frac{(\bar{R}\gamma_e)_{lat}}{(\bar{R}\gamma_e)_{ea}} - \bar{G}_T \frac{c_{R\ lat}}{c_{R\ ea}}} \qquad (2.1)$$

where G_{cp}, G_{af}, G_{eq} and G_{fit} are the weight of the commercial payload, airframe, equipment and fittings. The "ea" and "lat" indices indicate characteristics of engines in the earlier and later stages of their development.

7.2. Selection of the number of engines and power-to-weight ratio of the airplane. The number of engines and the required power-to-weight ratio are determined, as is known, by conditions of a completed takeoff with the failure of one engine and provision for a normal degree of safety or (for a two-engine airplane) conditions of an aborted landing, i.e. climb-out for a second circuit with one engine shut down; balanced field length, i.e. a set airport class; sometimes by conditions of cruise; the achievement of maximum effectiveness of the airplane; and limits in the level of noise from the airplane in the area of the airport. In selection of the number of engines, conditions for providing power for the airplane systems, such as the hydraulic, electric, air conditioning, anti-icing and others in case one of the engines fails is also looked at.

A completed takeoff with the failure of one engine is determined by a normalized value for the gradient of speed during climb V_y/V_2 at an altitude of 10.5 m (above the landing field level),

which is the criteria for the degree of safety required for an airplane to be airworthy. In other words, with the selected values for the total engine thrust and wing area, the maximum takeoff weight is limited by the value of this gradient. At the same time, the capability of the airplane for operation from a definite class of airport is determined by such takeoff and landing characteristics of the airplane as runway length (at maximum weight of the airplane). Consequently, a low class airport can lead to limiting of takeoff weight and nonusage of its maximum productivity.

The value for the V_y/V_2 gradient must be no lower than that established by international norms for airplanes with two, three and four engines at 2.5, 2.7 and 3 respectively. With determination of its value for an actual airplane, the angle of flap extension (δ_{flap}) and the time for gear retraction are calculated. With a decrease in these values, the gradient increases. In this manner, the number of engines (n_e) and the power-to-weight ratio ($\bar{R}$) determined by these conditions are related by the equation /96

$$\bar{R}_{n-1} = \frac{V_y/V_2 + 1/K_{V_2}}{\Delta^V_R}; \quad \bar{R} = R_{n-1}\frac{n_e}{n_e - 1}, \tag{2.2}$$

where $\bar{R}_{n-1}$ -- power-to-weight ratio upon failure of one engine; V_y -- vertical velocity component at climb; V_2 -- safe takeoff velocity; K_{V_2} -- aerodynamic property corresponding to V_2; Δ^V_R -- drop in thrust according to velocity.

To determine the thrust required to continue the takeoff with one engine shut down, the following equation was proposed in the work of S. M. Yeger [18]:

$$R = \frac{n_e}{n-1} G_0\left(\frac{1}{K_{V_2}} + \sin\theta\right). \tag{2.3}$$

An increase in n_e (under conditions of maintaining $\bar{R}_{n-1}$) will lead to a decrease in the weight of the airplane, and until the appearance of engines with a high degree of by-pass, it also led to an increase (as a result of this) in its economy. On the other hand, increasing n_e complicates operation and increases expenses on servicing, which has the opposite effect on economy.

It is well known that any theoretical postulation of a question, as with a methodological development, becomes more convincing and finds traces of reality and practicality if it is accompanied by examples. Therefore, the question of the effect of the number of

engines and the power-to-weight ratio of an airplane on its weight effectiveness is illustrated with examples of its simplified solution to two problems. In the first of these (table 2.1), retention of takeoff weight was used as a condition, and in the second, maintenance of productivity was taken (see below). In determining the data in Table 2.1, the following allowances were made: wing area was kept constant; $\bar{R}$ was determined only by the value for the velocity gradient; m and γ_e were kept constant regardless of its thrust. Consequently, the results obtained are approximate.

TABLE 2.1.2 THE EFFECT OF THE NUMBER OF ENGINES ON THE LOAD RATIO OF AN AIRPLANE

Number of engines	n_e	4	3	2
Velocity gradient	V_y/V_2	3%	2.7%	2.5%
Power-to-weight ratio upon failure of one engine	R_{n-1}	0.173	0.170	0.168
Full power-to weight ratio	$\bar{R}$	0.230	0.255	0.336
Total thrust of the engines	nR	16100	17850	23500
Load ratio of the airplane	$\bar{G}_{ul}$	51.4%	50.4%	47.5%
Change in load ratio	$\Delta\bar{G}_{ul}$	—	—1%	—3.9%

From the data in Table 2.1 we see that the required thrust and load ratio in an airplane with a four-engine layout is close to that of a three-engine layout and differs significantly from that of a two-engine one. However, the latter also possesses a number of other advantages besides those operational and economic ones mentioned. A high power-to-weight ratio (with a full number of engines) provides: The possibility for significantly decreasing engine power settings immediately after takeoff, which reduces noise in the area around the airport; faster climb and smaller loss in fuel consumption in this configuration; the possibility for flying at high altitudes, which increases flight range at those altitudes at /97 which four-engine airplanes with a lower power-to-weight ratio also fly, but with lower engine power settings, as a result of which is is possible to increase their life. True, the amount of the latter to a large degree depends on flight configuration and, besides this, high throttle settings can lead to an increased specific fuel consumption during cruise.

A comparison of airplanes with different numbers of airplanes is given in the example (Table 2.1) only for the purpose of a general impression and an orienting quantitative evaluation. Therefore, the value for thrust is determined only under takeoff configuration conditions, which is, generally speaking, justified with moderate mechanization of the wing and engines with a low or medium degree of by-pass. (This was used as a condition in our example and is retained for all variations.) More widespread study with conditions close to actual design problems may, for instance, show the presence of a definite area for advisability of a number of engines, which was written about by professor A. A. Badyagin [3] and professor S. M. Yeger [18], justifiably relating the optimum number of engines with the duration of the flight and solving the problem from conditions not only of takeoff, but also of cruise characteristics.

The appearance of airbuses and wide fuselage long-range airplanes is related, as was mentioned, to the creation of giant engines (Fig. 2.5) with a thrust of up to 26,000 kg and with a significant decrease in specific engine weight and specific fuel consumption (this to a significant degree also compensates for the unavoidable power unit redimensioning with a sharp increase in the /98
power-to-weight ratio on two-engine airplanes). It is clear that for creation of a new type of passenger and cargo airplanes, new types of engines were also required. Simple improvement of existing ones could no longer lead to significant changes in the development of civilian aviation. A further problem was the perfection of engine aerodynamics and air intakes in connection with the high coefficient of by-pass.

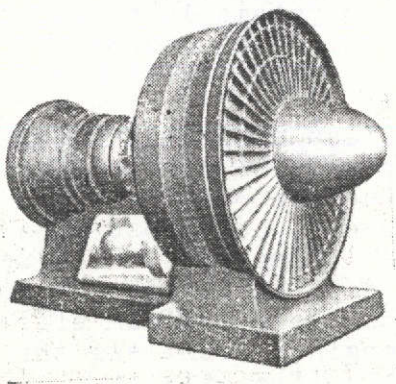

Fig. 2.5. Pratt-Whitney JT-9D turbofan engine with a by-pass of m = 5 and a thrust from 18,600 to 22,000 kg with various modifications.

With the creation of engines with a high degree of by-pass, the possibility arose for using the two-engine layout on airplanes weighing 120-140 t. On the other hand, with the appearance of the requirement for 250-350 seats on airbuses and 500 on giant liners, the possibility arose for using engines with high thrust, on which it was also possible to effectively realize a degree of by-pass of m = 5-6, i.e. to use the high degree of pressure increase, since the effect of an increase in π_k on engine characteristics increases with an increase in m. As a result of this, the two-engine layout was further developed, although it was disputed at first, as was

already mentioned. The dispute itself touched on the weight and economic effectiveness of a two-engine high-tonnage airplane and the degree of its safety. The operational features of this layout did not raise any doubt.

Representatives of some firms and the authors of a number of works thought that on short flights (2000-2500 km) and of course with an equal degree of safety, the two-engine layout possesses a significant advantage. Others did not find this advantage to be significant. Some also give preference to the three-engine configuration for airplanes of similar dimensions. Upon the selection of a two-engine configuration for the A-300 airbus (on its economic foundation), the possibility arose for using two of the engines which are used in a quantity of three on larger airplanes, and in a quantity of four on still larger ones. Dropping of the requirement to develop a new engine and a large series (as the result of unification) decrease expenditures on the power unit. The two-engine configuration is considered to be safer because of the /99
following considerations: such an airplane, satisfying requirements for the takeoff gradient, possess a higher power-to-weight ratio than one similar to it with four engines. Consequently, at the moment one of the engines fails, the airplane will have a large runway reserve to complete or abort the takeoff. Also, on the strength of these reasons, it will be easier for it to climb for a second circuit with all engines working. However, after landing with one engine out, difficulties arise. Limitations on the use of reversed thrust in this case must be more rigid. The problem of yawing with a different number of engines is solved in approximately the same way. With four engines, in cases of failure, the turning moment may prove to be high, but the correcting moment with reduction of thrust on the opposite wing will also be greater. The problem of reserves in equipment and control systems is satisfactorily solved on two-engine airplanes with only the presence of an auxiliary power unit (APU).

The three-engine configuration, regardless of its advantages, was not used in projects for short-haul airbuses of the A-300 type. The obstacle was actually related not to placement of the third engine (airbus fuselages have a large diameter), but arose as a result of the features shown for the engines themselves. The use of a three-engine layout is made more difficult on airplanes for which three engines with a thrust corresponding to their maximum effectiveness turn out to be re-sized. The use of engines with less thrust decreases the mentioned advantages only insignificantly.

This layout was used with large-dimension engines only in projects for airplanes with high total engine thrust (DC-10 and L-1011).

The three-engine configuration retains its domination in the rational decision of the question of power supply to the various airplane equipment systems in an emergency situation. This

circumstance has led to the appearance of the idea of an airplane with a configuration of "two-and-a-half" or "three-and-a-half" engine, in other words, a two-engine or three-engine airplane with a booster engine or starting accelerator. The additional or booster, small engine with a thrust significantly less than each of the main aones and a low degree of by-pass can easily be located inside the tail portion of even a small fuselage, and even more so in airbuses. The purpose of this engine is to increase the power-to-weight- ratio of the airplane upon failure of one of the main engines during takeoff and landing and to provide constant operation of the airplane system in these cases.[14] During cruise flight, the additional engine can be shut down or reduced to idle. This solution is apparently advisable but only for airplanes whose full-sized engines satisfy the requirements for cruising in their altitude-characteristics. With this layout, there must be absolute confidence in the second starting in view of the necessity for the additional thrust during an aborted landing for climbout for a second circuit with one engine not working. The layout with two-and-a-half engines is debased, consequently, on the compromise solution. Such an optimum compromise is attractive. Even with a small increase in total takeoff thrust (by 15-20%) through the installation of a booster engine, the relative value of its increase become essential at the moment one of the engines fails. In this definite case, it will increase by 30-50% (respectively with 3.5 and 2.5 engines). However, the advantages in the configuration with 2.5 engines are not limited to this -- the airplane acquires, as was noted, all the advantages of the three-engine configuration, in particular the triple back-up in the electrical, hydraulic, anti-icing and other systems[15]. The complexity consists of the requirements to: a) avoid an increase in the resistance of the nonworking engine during cruise; b) locate in one, and desirably an existing engine, capabilities for a powerful accelerator, starter, power source for air conditioning and for obtaining electricity with simultaneous satisfaction of the requirements for low noise and low fuel consumption. /100

An airplane with 2.5 engines turns out to be lighter than one with two engines for the following reasons. The inherent weight in the power unit is decreased as the result of a decrease in the required power-to-weight ratio, and the possibility arises for

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[14] [Translator's note: Unidentified footnote on p. 99: To be more precise, the upper limit of its usage (according to airplane tonnage)].

[15] To increase the reliability of these systems, their basic components are sometimes doubled. At the present time, for instance, three independent hydraulic systems are created on a three-engine airplane, and they work simultaneously and have a device for switching power sources to any of them in case an engine fails.

for eliminating the APU. True, a variation is also possible without removal of the APU, which in this case brings the configuration with 2.5 engines up to three. Finally, the additional engine with a well developed air intake can be used for extracting the boundary layer from the fuselage, which will lead to a decrease in frontal resistance. By the way, the weight advantages may also prove to be doubtful if the booster engine has a comparatively high specific weight. Operating costs with the 2.5 engine configuration will be lower due to a decrease in the cost of the power unit and, in particular, slow exhaustion of the life of the booster engine (in a case when it works only on takeoff and landing). The work of the remaining engines on takeoff with thrust somewhat lower than maximum, will also allow the life of these engines to be increased. Concerning airplanes having engines with a high degree of by-pass, it is doubtful that any one power setting, for instance, takeoff or cruise totally dominates the others in determining the required total thrust. Therefore, with the 2.5 or 3.5 engine layout, the additional one apparently must be capable of working in all regimes (and not only during takeoff and landing), but then the economic effect will be decreased. /101

In this way, the selection of the number of engines, especially for short-haul airplanes, just as the selection of its dimensions, is one of the most complex questions in planning. This complexity consists of the requirement for achieving high economy with absolute retention of the accepted level of safety. The two-engine configuration for the short-haul airbus is preferable both economically and operationally, but the old question -- is this configuration by its nature less safe than a three- or four-engine layout -- was again subjected to comprehensive research.

7.3. On analysis of the problem. It is possible to approach the solution of the problem on the number of engines from the point of view of effectiveness and safety in several ways. One of them is an investigation of the probability of failure on a basis, primarily, of operational data and statistics of failures[16] and accidents[17]. In this, the possibility for dangerous combinations of engine failure and other complicating pilotage factors such as, for instance, the absence of visibility and the possibility for combined failure of two engines are not overlooked. However, the comparison of statistical data on accidents of airplanes with varying numbers of engines is hardly correct, since the volume of movements on two-engine airplanes is immeasurably smaller. Another approach to the study, whose results are reviewed below, emanates from conditions of planning an airplane with an equal degree of safety at the moment an engine fails on takeoff with any number of engines. In a broad investigation, one should review the possibility for failure at all stages of a flight: on takeoff (continued

[16] Flight, Sept. 17, 1970.

[17] Airoplane, Nov. 3, 1966.

and interrupted), cruise (forced reduction in case one of the two engines fails) and during landing (climbout for a second circuit with one engine not working). It is also subject to a review of the possibility, connected to engine failure, of disruption in the electric power supply or in other systems. The serious and perhaps disputed question is that of whether or not it can be relied on that there is a lesser possibility of failure of one engine in two than of one in four. In the final analysis, the question comes down to evaluation of the means with which the required levels of safety and profitability are achieved. /102

There can be differences not only in the methods for solving problems and the depth of their workup, but also in conditions connected with the change in the various parameters of the airplane. In one case, with no changes, it is possible to use the takeoff weight (G) and commercial payload (G_{cp}) and determine the effect of the number of engines on flight range (L). In another, G_{cp}, L and L_{rwy} were considered set (which coincides with actual planning conditions), and the purpose of the analysis was to locate the minimum value for weight of the fitted airplane and operating costs. In the first approximation, in the analysis of short-haul airplanes the takeoff configuration was considered the determining one, supposing that a dangerous situation upon failure at cruise and during approach to a landing can be avoided by means of limitations. Thus, an equal degree of safety for climbout for a second circuit could in an extreme case be provided by limiting landing weight, sacrificing in the two-engine configuration (which possesses many advantages) the operational and economic advantages which are related to the small difference between takeoff and landing weights. Moreover, this sacrifice is not large, since the difference in the value for landing weight in two- and four-engine airplanes lies within limits of 3-4% for the example reviewed below. Concerning safety under cruise conditions, it is provided on engines with a high degree of by-pass by the fact that thrust changes as a function of velocity more sharply in them. Consequently, with a failure of one of two of these engines a relatively small decrease in velocity is sufficient to noticeably increase the available thrust, however without some decrease in flight altitude, this will apparently not do. All depends on the relationship between the characteristics of the engine and the wing. It has already been noted that imparting the necessary climb characteristics to a two-engine airplane will also promote satisfaction of the requirements for noise levels at airports.

For selection of the thrust-to-weight ratio, related to selection of the number of engines in long-range airplanes, conditions of a takeoff with failure of an engine (climb gradient and runway limiting) loses its meaning as the degree of by-pass increases and ceases being a limiting factor[18]. The factor of how much natural

[18] For short-haul ones, usually based on airports with short runways, the takeoff configuration remains the limiting factor.

drop in thrust with an increase in altitude and velocity will satisfy requirements for cruise flight with aerodynamic properties close to the maximum value at an assigned flight level acquires the primary meaning.

Approximate analysis of the short-haul airplane can be limited to review of two of the more interesting questions: under what conditions does a changeover from four engines to two not decrease economy and what effect does selection of the number of engines and their technical perfection have on economic effectiveness? To clarify these questions, two hypothetical airplanes are reviewed with engines corresponding to the technical level of the first and third generations, which to a significant degree guarantees correctness of the comparative analysis. The first of these is the DeHavilland "Comet" type (72.5 t) with engines similar to the Rolls Royce "Evon" (i.e. single-flow). The other was a A-300 airbus type (120 t), with by-pass engines (with different degrees of by-pass (m) depending on the amount of thrust) type RB-163-50 "Spey" (m = = 1); RB-178 -- decreased (m = 3) and JT-9D-1 (m = 5). The various values for the size of m were selected with consideration for the reasons presented above on the possibility for the realization of m = 5-6 with R = 10,000-12,000 kg only with a lower value of π_k, than in engines with a thrust of 18,000-22,000 kg, and consequently also with a higher specific fuel consumption (in engines with lower thrust). When reviewing engines with different values for m, considerations were also made for different drops in thrust (Δ_R^V) as a function of velocity[19], which is determined according to the approximation formula of V. S. Khukhorev for the takeoff condition (M = = 0.1-0.2; H = 0). /103

$$\Delta_R^V = \frac{R_{rot}}{R_{st}} = 1 - M(0.5 + 0.11m). \qquad (2.4)$$

The following were used as conditions for analysis: equal productivity for all variations of each of the airplanes; an equal degree of safety, determined by the gradient of climb and the placement of engines, of a single type and with any number. The cost was determined according to the method of E. A. Ovrutskiy [3]. Due to the difficulties in obtaining reliable information, the data should be reviewed as comparative.

The first condition -- productivity -- was taken in accordance with the selected prototypes which had: G_0 = 72.5 t, G_{cp} = 10 t, L = 4400 km; G_0 = 120 t, G_{cp} = 27 t, L = 2500 km. The character of the productivity of these airplanes is not identical. The first of these has a relatively low load and reasonably long range, while

[19] The drop in thrust according to temperature was not considered, since it relates not to the degree of by-pass but to the design of the engines.

those of the second were reversed, but this did not affect the results. At the same time, each of these airplanes is typical for its period in the development of aviation.

Review of a similar problem begins with determination of the power-to-weight ratio, and computation of the weight characteristics of the airplane boiled down to finding the relative weight of the power unit, the required fuel reserve and the takeoff weight for the airplane. The relative weights of the airframe and equipment in airplanes with turbofan engines are changed insignificantly, /104 since the takeoff weights are very close, and in variations with single-flow engines, they are changed significantly, which is taken into consideration in the analysis presented. Its results are presented in Table 2.2, in which data from the two initial variations are taken as 100%.

TABLE 2.2. EFFECT OF THE NUMBER OF ENGINES ON AIRPLANE CHARACTERISTICS

Type of engine	Single-flow			Turbofan			
Number of engines	4	3	2	4	4	3	2
Degree of by-pass	0	0	0	1	3	3	5
Power-to-weight ratio in %	100	112	146	100	105	116	160
Takeoff weight in %	100	104	117*	100	97,5	98,4	98,5
Weight of equipped airplane in %	100	105	123	100	98	99,5	105
Relative weight of fuel and power unit in %	100	102,5	110	100	94,5	95	98,5
Load ratio in %	53	52,5	50,8	46	44,5	44,3	42,1
Cost per ton kilometer in %	100	102	113*	100	93,5	94	91,4

*In recalculation from conditions of L_{rwy} = const, the increase in weight is 28%, and that in cost is 22.5%, since the required power-to-weight ratio in this case increases by almost 70% (instead of 46%).

Review of this table allows some conclusions to be drawn.

1. The required power-to-weight ratio with a changeover from two engines to three increases insignificantly, and with a changeover to two engines, it increases essentially. With turbofan engines, the increase is more significant, which is explained by a large gradient for thrust drop as a function of velocity.

2. With turbofan engines, a changeover from four to two almost makes no change in the takeoff weight. The weight of an equipped airplane somewhat increases and, despite this, economy is improved. For single-flow engines, the results turned out to be contrary, which also explains the limited usage of the two-engine configuration in the past.

3. Cost, practically equal in the variations of m = 3 and m = 5, proved to be lower than in the initial variation with m = 1. /105
With a strict calculation of expenses for servicing the engines, this decrease is even more significant.

4. The load ratio with a decrease in the number of engines is decreases as the result of an increase in the weight of the power unit and a decrease in the weight of fuel. In this case, this proves to be favorable, since productivity and the commercial load ratio are maintained.

A change in the load ratio with a change in the number of engines is found under two different conditions (G_0 = const and $G_{cp} \cdot L$ = const), which are found in Tables 2.1 and 2.2. With this, in the second of these it is shown with an example of airplanes having engines of a different technical level. The data obtained is presented in Fig. 2.6, on which are drawn four statistical curves of the change in load ratio of airplanes with different number of engines (1-4) and two curves (a and b) which were obtained analytically for the two airplanes mentioned. The conditions of equal productivity and an equal degree of safety were used during computation of these curves.

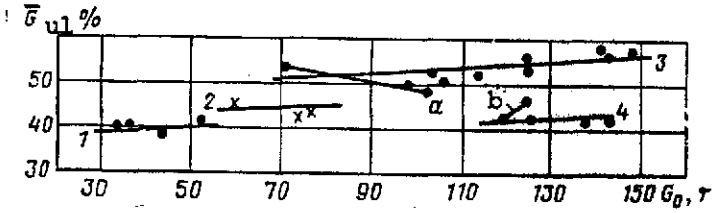

Fig. 2.6. Load ratio of two-engine (1), three-engine (2), four-engine (3) airplanes and two-engine airbuses (4). Change in the ratio with a change in the number of engines on an airplane (a) and an airbus (b).

From a review of Fig. 2.6 and the data in Tables 2.1 and 2.2, we see that engine perfection has a noticeable effect on the load ratio of a passenger airplane. With a decrease in the number of engines from four to two (with $G_{cp} \cdot L$ = const), the change in takeoff weight and load ratio depends on the degree of perfection of the engines. Thus, in airplanes with single-flow engines, the takeoff weight increases sharply with a simultaneous drop in the load ratio. In

airplanes with by-pass engines, the takeoff weight is almost unchanged, and the load ratio is decreased[20], but in this case it does not deteriorate the weight effectiveness.

In a brief review of the problem of selecting the number of engines and with the comparison of analysis results, an attempt was made to explain the tendency toward decreasing the number of engines (in airplanes of comparable tonnage) as the degree of by-pass decreased, and also to track the reasons for an increase in the power-to-weight ratio, especially in two- and three-engine airplanes. It is clear, naturally, that with a different formulation of the problem than was used in our example, or with consideration of a larger number of factors which affect the economic effectiveness of airplanes, it would be possible to obtain results which differ from those presented above. However, the major result under any conditions will be the same. This is namely: with the development of turbofan engines, airplane configurations having different numbers of them (two, three or four) will become ever more evenly expensive. Jumping somewhat ahead, it is possible to say that the matter concerning various arrangements of engines on airplanes will prove to be similar. /106

Analysis of the problem on a number of engines explains the tendency for decreasing their number with an increase in the degree of by-pass and supports the position that an increase in the power-to-weight ratio without harm for economy is possible with new qualitative leaps in engine development.

The weight of the power units on the airplanes analyzed is determined according to a formula, which is presented for the purpose of considering the peculiarities of various layouts (K_ℓ) of engine arrangement (on the wing, on the fuselage, mixed), the effect of the number of engines (K_n)[21] and the number of reverses (K_r). The degree of by-pass and other engine parameters are considered through their specific weight (γ_e). For single-type installations (all engine totally equal and all on the wing or on the fuselage), it looks like

$$G_{pu} = \xi K_\ell^{pu} K_n K_p (0.2 + 1.7\gamma_e^2) R_{n-1} \frac{n}{n-1} + aG_0. \qquad (2.5)$$

With mixed power units (two on the wing and one on the fuselage or with $n_e = 2.5$), the formula will look like

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20 By comparison with the four-engine airplane with m = 3.

21 The value of K_n corresponds to the condition of $\bar{R}_{n-1} = \text{const}$.

$$G_{pu} = [\xi K_{\ell}^{pu} K_n K_p (0.2 + 1.7\gamma_e^2) R_n]_{EbW} + \quad (2.6)$$

$$+ [K_{\ell}^{pu} K_p' (0.2 + 1.7\gamma_e^2 R]_{EoF} + aG_0,$$

where R_{n-1} -- thrust upon failure of one engine; n_e -- number of engines; $\bar{\xi}$; a -- statistical coefficients (see Table 2.3); K_r -- coefficient considering the number of reverses; K_r' -- coefficient considering the presence of reverse on the third engine with their mixed placement. (With its presence $K_r' = 1.07$ and in its absence $K_r' = 1$.)

Using Eqs. (2.5) and (2.6) it is possible to determine the weight of the power units in the standard configuration, but without considering the weight of the fuel system, the unusable fuel remaining and the acoustical lining in the pods. These equations are applicable to power units with by-pass engines and a degree of m lying within limits of from 0 up to 5-6. Eq. (2.7) also does not consider the weight of the unusable fuel remaining.

The weight of the fuel system is determined by the equation /107

$$G_{fs} = (0.0127 - 0.017 \cdot 10^{-6} V_{fs})(0.68 + 0.27 K_{\ell}^{fs}) V_{fs} \quad (2.7)$$

where K_{ℓ}^{fs} equals 1.0 for airplanes with engines beneath the wings (EbW); K_{ℓ}^{fs} equals 1.2 for airplanes with engines on the fuselage (EoF); V_{fs} -- fuel system volume in liters.

The error in formulas (2.5) and (2.7) lies within limits of $\pm 5\%$.

7.4. Dimensions and configuration of the fuselage. The problem of selecting a configuration for the fuselage and the number of decks arose when an essential leap in the change in its dimen- /108 sions occurred. Only one factor -- passenger placement -- had an effect on selection of dimensions during the piston aviation period. Conditions related to this include: seat width and leg room between rows, width and height of the aisle and, depending on the number of passengers, the number of toilets, wardrobes and entry doors. Naturally, the spaces formed in the subfloor and tail sections of the fuselage were practically sufficient for installation of the baggage compartment there. During the period of gas turbine aviation, the dimensions of the fuselage cross section increased along with the increase in passenger seating capacity, and the number of seats in one row increased from 3-4 up to 5-6. The latter value was acknowledged as the limit for cabins with one aisle. However, in this period, the increase in cargo movements also began to have an effect on choice of fuselage configuration. Designers were forced

to increase the height of the cross section (by increasing the baggage compartments in the subfloor space), whose shape began to be formed from arcs of circles (Fig. 2.7). A review of the evolution of fuselage configuration over several decades shows that changes took place gradually, with only dimensions increasing (Fig. 2.7). At the same time, the appearance and technical characteristics of airplanes changed essentially over this period.

TABLE 2.3. VALUE OF CALCULATED COEFFICIENTS IN EQS. (2.5) AND (2.6)

Coefficients			Number of engines							
			Engines beneath the wing		Mixed arrangement* with placement of third engine			Engines on the fuselage		
					In the fuselage		On the fuselage			
Number of engines			2	4	2,5	3	3	2	3	4
ξ			1	1,03	—	1,0	—	1	1,03	1,03
K_{ℓ}^{pu}	Powered pods beneath the wing and pods on the fuselage		1	1	0,99	0,99	0,98	1,04	1,01	1,06
	Unpowered pods beneath the wing		0,98	0,98	—	—	—	—	—	—
K_n			1	0,95	—	0,975	0,975	1	0,975	0,95
K_r	Grate reverse	with $n_r=2$	1,07	1,035	1,0	1,0	1,0	1,07	1,052	1,035
		with $n_r=n_e$	1,07	1,07	1,07	1,07	1,07	1,07	1,07	1,07
	Vane reverse	with $n_r=2$	1,11	1,055	1,0	1,0	1,0	1,11	1,083	1,055
		with $n_r=n_e$	1,11	1,11	1,11	1,11	1,11	1,11	1,11	1,11
a			0,005	0,005	0,003	0,005	0,005	0,005	0,005	0,005

* Two engines beneath the wing, one on the tail

Cargo movements increased the possibility for using the load capacity in passenger airplanes on routes (or during seasons) with a decreased value for the coefficient of passenger loading. Therefore, the effect of these movements on the selection of dimensions and configuration also increased. During the planning of third generation airplanes, the required value for the total commercial

payload and the number of passengers reached limits such that their placement in typical fuselages already proved to be impossible. Besides this, the increase and conditions of cargo movements required the organization of their transportation in containers, whose dimensions moved out of the limits of possibility for operational airplanes. As the result of these two reasons, a problem also arose concerning selection of the optimum configuration for a large-dimension fuselage on the basis of the criteria of minimum design weight, maximum airplane economy and simplicity of operation. /109

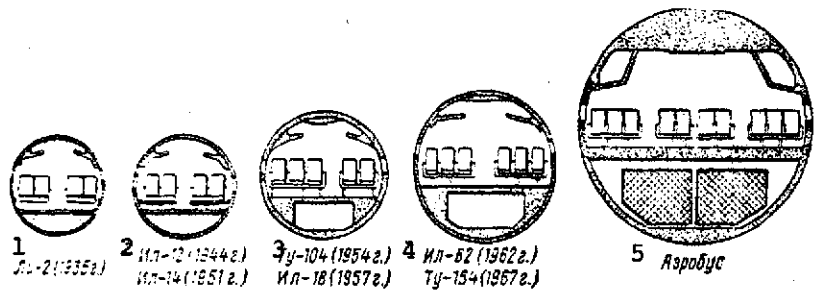

Fig. 2.7. Cross sections of passenger airplane fuselages.

Key: 1. Li-2 (1935)
2. Il-12 (1944); Il-14 (1951)
3. Tu-104 (1954); Il-18 (1957)
4. Il-62 (1962); Tu-154 (1967)
5. Airbus

7.5. Extended length fuselages and multidecked fuselages. The appearance of large-dimensioned fuselages (beginning at 250 passengers) actually began with the so-called "stretched" fuselages which retained the single aisle layout but differed in a significant increase in length ($\lambda_f = \ell/D$). While its size for the majority of operational airplanes lies within limits of 9-12, for the stretched ones, λ_f = 14-15. The creation of such fuselages, which are narrow tubes up to 60 m long was connected with the solution of a number of problems in arrangement, centering of gravity, rigidity, design weight and control dynamics. In weight relationship, fuselages with large values of λ_f are unprofitable, since with a given cross section the stress from flexion increases proportionally to the square of the length of the fuselage. The height (h_g) and the weight of the gear were increased to meet conditions of retaining the landing angle (α_{ldg}), or α_{ldg} was decreased with h_g = const.

High values for λ_f will lead to an unfavorable (with regard to aerodynamics and weight) relationship between surface and volume, limit the possibility for increasing comfort up to the modern level and aggravate the "tunnel" effect (or create a "tubular" effect).

The latter is characterized by the value which a lengthened cabin (salon) is sometimes called, i.e. the relationship of width to height. This value usually lies within limits of 0.2-0.3, but on modified airplanes with an increase in fuselage length (of the type DC-8-61), it is reduced to 0.1. Operating conditions are also deteriorated, in particular the rapid seating of passengers, their exit from the airplane and evacuation in case of emergency. As a result of the aforestated, the values presented for lengthening the fuselage λ_f (14-15) and the number of passengers (250 persons) are for narrow fuselages apparently the limits and are encountered only on modifications.

Increasing the fuselage length is hindered not only by an extreme value for λ_f, but also by the relationship between wing area (S) and fuselage length (ℓ_f) and the centering problem related to it. This becomes apparent if we recall that fuselage diameters with S_1 = 260-300 m^2 and with S_2 = 130-150 m^2 are equal. Consequently, the relationship between λ_f and S comes down to the relationship between ℓ_f and S. As regards centering, with a small S, the mean aerodynamic chord is also small, and with a large ℓ_f, the moments from the commercial payload are high, and consequently the displacement of centering and the distance from the takeoff position of the CG to the axes of the main gear wheels are also increased. This condition and the decreasing pressure on the nose gear, which reduces maneuverability of the airplane on the ground, may prove to be the limiting factors on increasing fuselage length.

Another solution to the problem of the multiseat fuselage consists of increasing the diameter while reducing or maintaining λ_f, which promotes transfer to a multi-deck arrangement of the cabin (Fig. 2.8). Fuselage layouts are divided according to number of passenger decks into one-, two- and multi-deck, while the sub-deck cargo compartments are not commonly counted as decks. An airplane with a two-deck fuselage may be very close to the mid-wing layout, which leads to a decrease in the height from the ground to the entry doors, allows the use of small built-in gangways and is more easily re-fitted into the cargo-passenger variation. The acceleration in loading and unloading with this to a large degree corresponds to the idea of the airbus. True, the wing center section increases, although losses in flight speed are not so great. In the weight relationship, the two-deck fuselage with 220-250 passengers is approximately equal to the single-deck one. With a higher number, the effectiveness of the two-deck layout increases. Therefore, the decrease in aerodynamic quality and the corresponding overconsumption of fuel may be compensated by a decrease in design weight. The essential deficiency in the two-deck layout is the limited possibility for storing baggage and cargoes, which hinders its use for airbuses. The above is true for comparison of single-aisle fuselages. /110

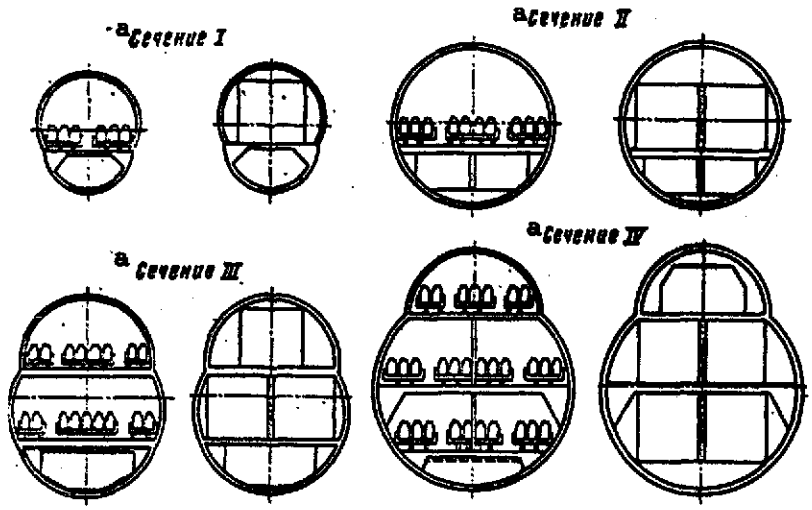

Fig. 2.8. Variations in cross sections of single- and multi-decked large-dimensioned fuselages[22].

Key: a. Section...

Arrangement of cabins in large-dimensioned fuselages according to the single- or multi-decked layout depends, as does configuration, not only on placement of passengers. The relationship between the required spaces in the passenger cabin and the baggage-cargo compartments has an effect on solution of this problem. Section shapes of various fuselage variations obtained with consideration for these requirements are presented in Fig. 2.8. They are circumscribed around containers and a corresponding number of seats. For two-aisle fuselages with consideration for this factor, the multi-deck diagram leads to a decreased design weight with a passenger seating capacity of over 500 persons. True, multi-deck fuselages in such airplanes will create new problems in connection with their servicing at airports and evacuation of passengers. The multi-decked layout (with two-aisles) may prove to be preferable for a short-haul airbus having 300-350 seats, if it is recognized that the flow of cargoes (on short routes) will be insignificant. /111

7.6. The fuselage with two aisles. Increasing the cross section of a fuselage will lead to the requirement for arrangement of seats with two aisles (see Fig. 2.8), since conditions for providing convenience for passengers and the work of the stewardesses is limited by the number of seats in one row, and the limit for their placement in a cabin with a single aisle is considered to be six. It has become apparent at the present time that the fuselage of the shape accepted earlier cannot satisfy the requirements for the

[22] Section diagrams -- from work [70].

increase in cargo and passenger room in future airplanes. Another thing has become clear -- the single-deck fuselage will reach its limit in space immediately upon development of large-dimensioned airplanes of the third generation. A further increase will require use of multi-decked fuselages, which must lead to an increase in the airplane's economy. In this way, the dimensions and configuration of the fuselage, like, by the way, the layout of the entire airplane, will to a significant degree be determined by technical requirements. Indeed the task of planning will consist of finding the optimum solutions allowing fulfillment of these requirements with the least weight and minimum operating expenses. At the same time, wide fuselages introduced great weight losses, and complexity in solution of one of the main problems of the airbus is connected with this.

The basic conditions in selecting fuselage configuration include: determination of the number of passenger seats and cargo containers located in one row, finding the required section and the smallest perimeter for their placement; determining the space in the nose and tail portions of the fuselage; determining the length of the cylindrical portion; and determining the weight and frontal resistance of the fuselage.

In the selection process, a number of variations are looked at and optimization of the previously selected prototype is conducted[23]. Weight and frontal resistance of the fuselage can be taken as criteria for optimization[24]. In this, their effect on the change in engine thrust and wing area and, consequently, the change in the weight of the airplane as an aggregate of all these changes are considered. A similar solution is true if the commercial payload, number of passengers and flight range are given, and all other factors (thrust of the engines, dimensions of the airplane) are variable. Another formulation of the problem is possible, for instance, the thrust being given (engines selected from existing ones) and the determined factor is the maximum commercial payload or flight range. Inasmuch as with a large number of passengers, one- and multi-decked variations are being looked at simultaneously, it is convenient to express the change in fuselage weight as a function of the total area of the lateral (wetted) surface and area of the floor. With a change in fuselage length, a change in the dimensions and weight of the tail empennage is considered from conditions of maintaining the static moment. Below is presented a method for calculation proposed by Morris and Ashford [70] and graphs constructed by them, onto which points corresponding to the Il-18 and Il-62 have been additionally placed. Coincidence with data from the Douglas airplane firm, according to whose materials the curves were constructed, shows that the density of arrangement and the weight

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[23] See Chapter 19.

[24] It is also possible to optimize on the basis of economic criteria.

effectiveness of the fuselages lie on the same level. The authors recommend examination not of the actual weight of the fuselage (G_f), but also consideration in this of the total weight of standard equipment (G_{se}):

$$G_f + G_{ne} = K(S_{fw} + \Sigma S_{fl}), \qquad (2.8)$$

where S_{fw}; S_{fl} -- areas of the lateral surface of the fuselage and floors of all decks; K -- coefficient of proportionality.

They recommend that the value for coefficient K in the first approximation be taken as 29.3 kg/m^2 for long-haul airplanes; and 26.8 kg/m^2 for short-haul airplanes (in which there is a smaller volume of equipment). The dependency of these values is presented in Fig. 2.9. Section dimensions are determined, as is known, by initial points connected with the height of the aisle and the width of the floor. The latter depends on the number of seats in a row (Fig. 2.10) and the number of aisles. Multi-decked fuselages have somewhat larger floors than single-decked ones (with the same number of seats) due to curvature of the sides. A definite conformity exists in the change in the equivalent diameter (diameter of an equal sized circle) due to the number of seats in the fuselage section (Fig. 2.11). The dependency of the center section area (F_c), and, in the final analysis, the wetted surface of the fuselage on the number of seats is expressed in the form of area and perimeter of the cross section (Fig. 2.12). The length of the perimeter /113 for a single-deck fuselage has a limit equal to 1.8 m per one seat, which is obtained by multiplying the number π by the minimum width of the floor belonging to one seat. The amount P/m_{st} for multi-decked fuselages is decreased (see Fig. 2.12). Consequently, for a number of passenger seats in one row over 10, the cross section of a multi-decked fuselage has a smaller perimeter than that of a single-decked one, from whence there is a lower weight and a lower frontal resistance. This difference becomes essential with the installation of more than 15 seats in a section. Examination of the/114 graphs presented will lead to a conclusion that with an increase in the number of seats in row, the density of arrangement in a cross section and its effectiveness will increase.

In determination of the fuselage dimensions, it is possible to determine its cylindrical part analytically, and the shape of the nose and the tail portions are determined through extension. The value of the latter is taken as equal to $\lambda_{np} = 2$ for the nose portion and $\lambda_{tp} = 3$ for the tail portion. The weight of these portions is determined according to the graph on Fig. 2.13, which was constructed for the four sections whose form is presented in Fig. 2.8. From the graph (Fig. 2.13), it follows that with an increase in cross section volume, the total weight effectiveness of the nose and tail portions of the fuselage is improved. After the shape and dimensions of the cross section have been selected and the amount of

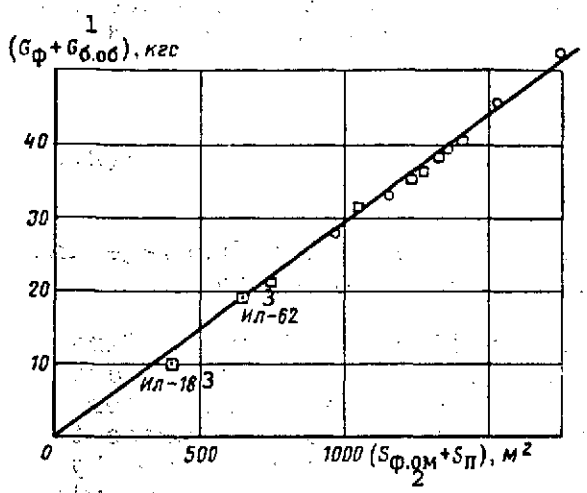

Fig. 2.9. Dependency of the weight of the fuselage and normal equipment on the total area of the lateral surface of the fuselage and the area of the floor; □ -- single-decked; o -- multi-decked.

Key: 1. (Gf + Gne), kg; 2. (Sfw + Sfl), m²; 3. Il...

of load located in the nose and tail portions of the fuselage has been found, finding the length of the cylindrical portion of the fuselage does not present difficulty. To determine the weight of the equipped fuselage (as a function of the number of passengers) and its frontal resistance, graphs were constructed (Fig. 2.14). It has already been noted that the weight of the fuselage cannot be determined without considering the effect of its length upon the dimensions and weight of the tail structure. For determining this effect, graphs expressing the dependency of the static moment of the horizontal (A_{hs}) and the vertical (B_{vs}) stabilizers on the geometric parameters of the airplane are constructed (see Chapter 16). /115

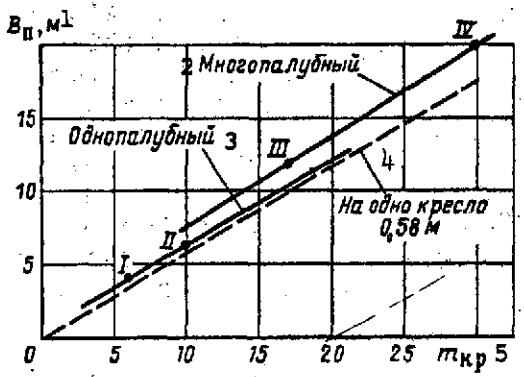

Fig. 2.10. Dependency of floor width (B_{fl}) on the number of seats in a cross section (m_s); section I-IV (see Fig. 2.8).

Key: 1. Bfl, m; 2. multi-decked; 3. single-decked; 4. 0.58 m per one seat; 5. m_s

Analysis of the examined method [70] allowed its authors to draw the following conclusions.

1. For a given cross section, a long fuselage has a relatively lower weight and frontal resistance than a short fuselage. This is explained by th e fact that the effective cylindrical portions in long fuselages occupy a relatively higher volume. Besides this, with an increase in the fuselage, the Reynolds number increases, leading to the decrease in the coefficient of friction for the skin. And vice versa, very short fuselages are not effective due to the fact that the nose and tail portions predominate in them. It is evident from Fig. 2.14 that a lengthening of a fuselage equal to approximately seven is the practical minimum limit. /116

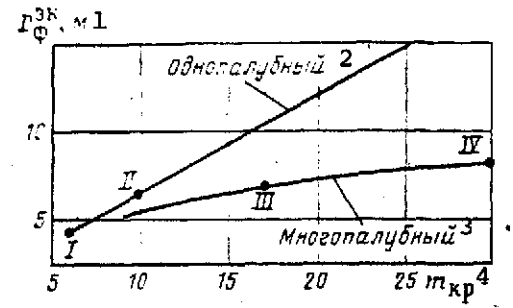

Fig. 2.11. Change in equivalent diameter in dependence on the number of seats in one row; sections I-IV (see Fig. 2.8).

Key: 1. D_f^{eq}, m; 2. single-decked; 3. multi-decked; 4. m_s

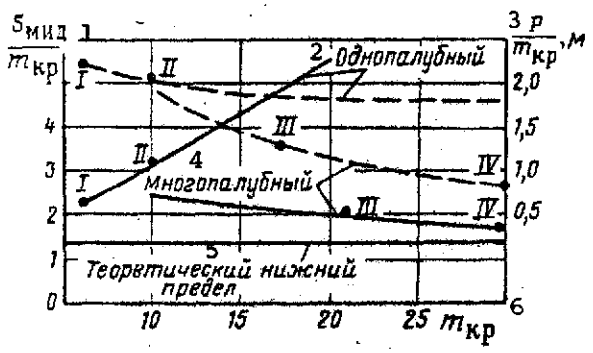

Fig. 2.12. Dependency of center section area and cross section perimeter length belonging to one seat on the number of seats in the section (m_s); sections I-IV (see Fig. 2.8).

Key: 1. S_{ctr}/m_s; 2. single-decked; 3. P/m_s, m; 4. multi-decked; 5. theoretical lower limit; 6. m_s

2. When the single-decked and multi-decked fuselages are compared, the difference in weight and frontal resistance between "acceptable" fuselages calculated for a set payload is not great. The term "acceptable" fuselage is understood to mean a fuselage with a length lying within limits bounded by a lengthening of seven and landing angle of 12°. In this way, after selecting a cross section for fuselages of a given volume, those fuselages which are "unacceptable" can be eliminated and the remaining fuselages are subjected to detailed analysis.

3. The three-decked fuselage of future airplanes with a passenger seating capacity of 1000-1100 persons will differ from the fuselage of the modern DC-8 airplane (holding 189 passengers with lower values for weight and frontal resistance attributable to each passenger by 40 and 50% respecitively. From this it is possible to draw the conclusion that effectiveness will also increase with a further growth in airplane dimensions.

7.7. Fuselages with few seats. The problem of selecting fuselage configuration is not bounded by the limits of large-dimension multi-seat airplanes. Its meaning is also retained for small airplanes on short main lines and local lines holding 100-140 passengers of the "Mercury" type (France) and small, for instance, 40-place airplanes with a flight range of 600-800 km. The requirement for tranporting cargoes on standard pallets in cargo-passenger variations is also set forth for these airplanes. The latter affects selection of shape and arrangement of the fuselage. In these cases, fuselage configuration is usually

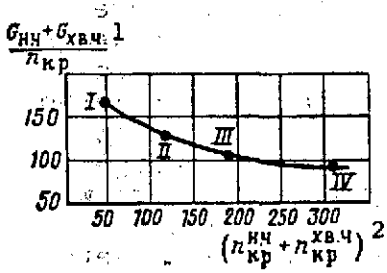

Fig. 2.13. Passenger seating capacity and weight of the nose and tail portions of fuselages of various sections; sections I-IV (see Fig. 2.8).

Key: 1. $\frac{G_{np}+G_{tp}}{2\,(n_s^{np}+n_s^{tp})^{n_s}}$

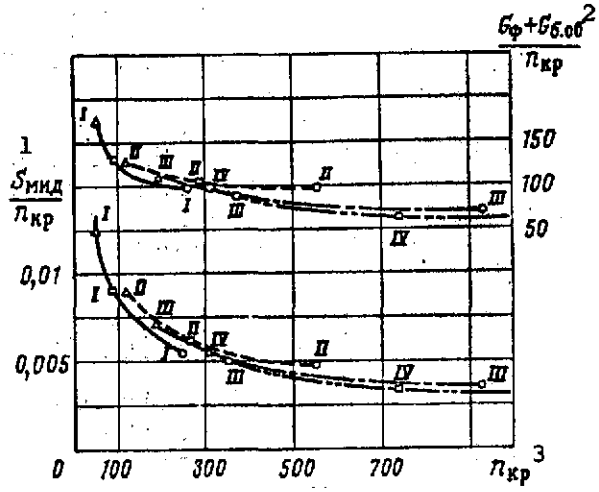

Fig. 2.14. On determining the weight and frontal resistance of the fuselage: Δ - all passengers in the nose and tail portions; □ - limitation of $\lambda_f \geq 7$; o - limitation of $\alpha_{ldg} \geq 12°$; sections I-IV (see Fig. 2.8).

Key: 1. S_{ctr}/n_s; 2. $\frac{G_f+G_{ne}}{n_s}$ 3. n_s

optimized with a circle with a cross section which is most advantageous for these sizes and type [75]. Unchanged previously-determined dimensions and layouts for the remaining portions of the airplane, and also aerodynamic parameters of the airplane and specific engine characteristics are taken as other prerequisites. The weight of the fuselage and airplane, resistance and engine thrust are taken as changeable.

The dimensions of the fuselage are determined by the set number of passengers and standard pallets, on which the length and diameter of the cylindrical portion depend. The usable floor area in the nose and tail portions is considered to be auxiliary and baggage compartments, and a partial row of seats is located there. The values for λ_{np} and λ_{tp} in analysis are taken as variable with the relationship between them retained. The weight of the fuselage is determined as the sum of two groups. The weight of the first includes those parts whose weight depends on λ_f, namely the weight of the skin, stringers, frames, window frames, floor and pressure barriers. The effect of internal pressure in the pressure cabin is considered with a weight correction, and the weight of the doors, partitions, lights and fuselage joints with the wing, empennage and nose leg of the gear are taken as constant. /117

The takeoff weight of the airplane is naturally changed with a change in fuselage weight and its resistance. The effect of these factors is established with a coefficient of increase. An increase in resistance necessitates the requirement for an increase in available engine thrust. An increase in their weight and

required fuel reserve (from conditions of set flight and takeoff and landing characteristics) is connected with this. An increase in weight because of engines, fuel and fuselage should be viewed as a first order weight increase, which, through the increase of all weights depending on it, causes a second order weight increase (see Chapter 9.4). Fuselage resistance, along with its weight, must be examined together with consideration for the effect of the tail empennage. With this, it is recommended that only friction resistance and resistance of form be considered.

7.8. Space arrangement. The results of analyses similar to those examined above or any others are usually conducted according to statistical materials and by means of immediately tracing out the analyzed variations. Statistical materials are used in the form of absolute and relative amounts, and also in the form of statistical equations. The latter consider the conformities of change in these values with an increase in airplane dimensions. L. S. Zinin called a similar course for solving problems the method of space arrangement. Among the arrangement density criteria with which problems on the degree of fuselage space utilization are solved is the relationship of fuselage or cabin volume to the number of passengers. For large-dimensioned fuselages, the first of these criteria loses, to a known degree, its meaning. If the space in such a fuselage is examined only from conditions of passenger placement, the dimensions of its section and a single-deck layout will be shown to be advisable, since the part of the section occupied by passengers comprises only a small portion (see Fig. 2.7). Therefore, it is advisable to examine the usage of passenger and baggage compartments independently from each other.

It should be noted that for the purpose of maximum usage of wide-dimensioned fuselage volume and floor area, attempts are being made to reduce auxiliary compartments. Wardrobes, for instance, are not being constructed, and places by each seat and on shelves are provided for storing clothing. To the same end, the galley is located beneath the floor (delivery carts are brought up on elevators). Due to this, a significant number of additional seats appear (18-20 with a total number of 350). The arrangement of buffets in the cabin and even installation of part of the baggage /118
compartments there are not excluded for the sake of increasing cargo compartments. This all depends on requirements and actual conditions.

The dimensions of the airplane, its weight and economic perfection are affected not only by arrangement density but also by volume effectiveness, which is the relationship of the volume to the area of the wetted (washed) surface.

Contemporary requirements for fuselage planning include, as was recalled, conditions for transporting a significant cargo on flights with an underfill of passengers. In the meantime, fuselage dimensions are affected by selection of an economically expedient

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relationship of the weight of the passengers, baggage and cargo in the total weight of the maximum commercial payload (G_{cp}), which is determined by the coefficient $K_{cp} = G_{cp}/n_{pax}$. Its value depends on the dimensions of the airplane (Fig. 2.15) and affects the cost per ton kilometer. In examination of this effect, a definite contradiction is observed: the lower K_{cp} with the same total load, the higher the proportion of passengers in its total weight and economy is higher. With a set number of passengers and unchanged fuselage length, however, the maximum usage of the space will lead to an increase in K_{cp} due to an increase in cargo and will lead to an increase in economy. Methods for determining cost usually consider an average value for K_{cp} and are taken as equal to 120.

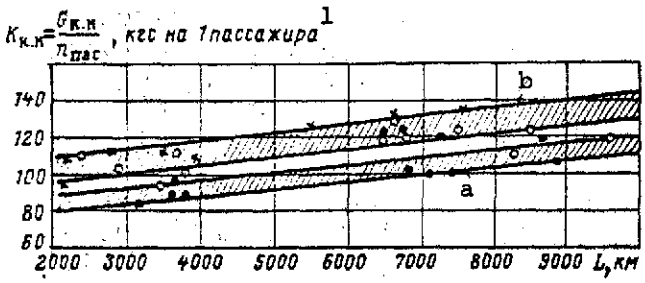

Fig. 2.15. Value of the coefficient of commercial payload: a - first and second generation airplanes in their initial variations (•); b - modifications (o) and third generation airplanes (x).

Key: 1. $K_{cp} = G_{cp}/n_{pax}$, kg per 1 passenger

An increase in fuselage length (with retention of its section), accompanying the tendency toward increasing passenger seating capacity, will lead to an increase in the relative value for the volume of the baggage and cargo compartments $\bar{V}_{bc} = V_{bc}/n_{pax}$, since the relative amount of the unused portion of the volume in the subfloor space is decreased. With an increase in the number of passengers, the value of K_{cp} increases commensurately. Keeping this in mind, as well as the future increase in passenger seats, the change in the value of K_{cp}, assigning it in the function of the number of passengers on the basis of the curves in Fig. 2.15 should apparently be considered. Selection of an economically rational value for K_{cp} is not limited by its effect on the value of the maximum commercial payload ($G_{cp} = K_{cp} \cdot n_{pax}$). It also has an effect on the degree of load capacity usage on flights with an underfill of passengers, which is determined from conditions of space and expressed with the coefficient of loading (K_{load}). The latter index affects economy, since the average annual value for the coefficient of passenger loading (K_{pl}) does not usually exceed 0.65. /119

Fuselage dimensions depend on the values for K_{cp}, γ_b, γ_c and q_b, with which the usage of the baggage and cargo compartments (V_{bc}) are tied. The dependencies of these values are expressed graphically in Fig. 2.16 and by equations (2.9), whose designations are presented in Table 2.4. This equation is correct for fuselages with $D \leq 4$ m and $n_{pax} = max$.

$$V_{bc} = \frac{(K_{cp} - 75)n_{pax}}{\gamma_{av}} \qquad (2.9)$$

where

$$\gamma_{av} = \gamma_c - \frac{\gamma_c}{\gamma_b} - 1 \quad \frac{q_b}{V_{bc}}$$

Here the density is not only the property of the cargo, but also of the compactness of packing. It also depends on the dimensions of the compartment.

7.9. Analytical determination of fuselage dimensions is based on statistical formulas [62]. The simplest of these has the appearance of[25] /120

$$l_f = 0{,}024 a_f \left(K_{cp} - \frac{K_{cp} - 75}{\gamma_{av}}\right) n_{pax} \qquad (2.10)$$

/A formula considering the types of loads and the number of crew members (n_{crew}), will lead to a more accurate determination of the required fuselage volume: /121

$$V_f = \frac{\psi}{K_{use}} \left\{ \left(K_{ad} + \frac{q_b}{\gamma_b}\right) n_{pax} + a_f K_{bf} \frac{[K_{cp} - (75 + q_b)] n_{pax}}{\gamma_c} + 2{,}46 n_{crew} \right. \qquad (2.11)$$

The values of the coefficients and their designations are given in Table 2.4.

The coefficients of volume usage and arrangement density of the cabin are determined with the equations:

$$K_{use} = \frac{V_{ad} + V_{ac} + V_{bc}}{V_f}; \quad K_{ad} = \frac{V_{ad} + V_{ae}}{n_{pax}}, \qquad (2.12)$$

where V_{bc}; V_{ac} -- volume of baggage and auxiliary compartments; V_{ad}; V_f -- volumes of the passenger cabin and fuselage.

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[25] Eq. (2.10) is also correct for fuselages with D > 4 m with $K_{cp} = 90.3 + 0.168 n_{pax}$, $\gamma_{av} = 225$ and a containerized system of loading.

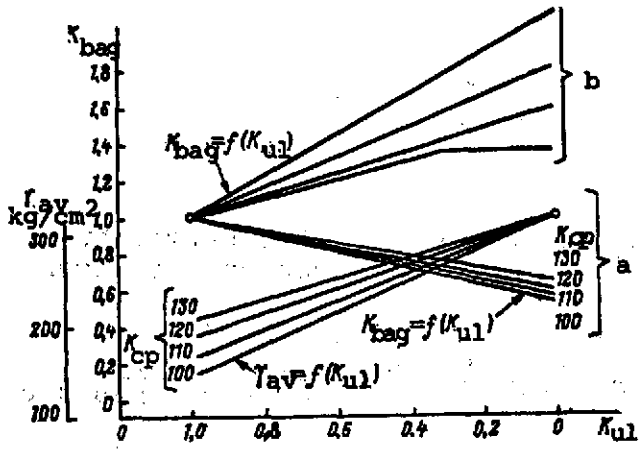

Fig. 2.16. Changes in the coefficient of loading of medium-density baggage and cargo with a decrease in the coefficient of passengers. a) passenger, and b) passenger-cargo airplanes.

Equation (2.11) is also valid for fuselages with $D > 4$ m.

Chapter 8. Problems in Economy and Safety

8.1. Economic effectiveness of airbuses. Various forms of passenger airplane effectiveness and evaluation criteria necessary for optimization are analyzed in detail in Chapter 18. The dynamics of these criteria in the process of aviation development are shown in Section 2.3. We are limiting ourselves here to an examination of the peculiarities of airbuses which have an effect on their economy. At first we recall that the term "economic effectiveness" defines an airplane capable of accomplishing cruise flight with a minimum cost per flying hour. (The coeffient of passenger loading, which determines only operating conditions, is not considered in this.) Cost per ton kilometer or passenger kilometer, and also the threshold of profitability defined by the threshold coefficient of loading (K_{tp}) or the number of passengers with whose transport the flight is justified $n_{pax} = A'/a_{af}$, where a_{af} is the average fare rate (in rubles) for a passenger hour of flight and A' is the cost of a flying hour are taken as criteria of effectiveness.

Economic effectiveness is reached only as a result of proper solution of all problems in planning and design. True, any part of these is also a determining factor. Thus, in development of the airbus projects, these included the problems of fuselage dimensions, and weight and resistance of the airplane. Optimization of the diameter and length of the fuselage and solution of the problem of space utilization were conducted on the basis of economic criteria. When arranging the cabin, naturally, requirements of comfort were considered. It was found, for instance, that the leg room between installation of the seats equal to 860 mm was a satisfactory compromise for both requirements, and that loading density in baggage compartments for European and American airbuses could be determined from conditions of transporting baggage in the quantity of 15 kg per single passenger. The loading density accepted also has a noticeable effect, since it determines not only the amount of the

required space in the baggage compartment but also the amount of commercial payload on flights with a number of passengers lower than the maximum, which comes out of the equation

$$G_{cp}=90n_{pax}-\gamma_c\left(V_{bc}-\frac{15\cdot n_{pax}}{\gamma_b}\right). \qquad (2.13)$$

TABLE 2.4. VALUES OF THE COEFFICIENTS FOR EQS. (2.9), (2.10) AND (2.11) UNDER VARIOUS CONDITIONS

Type of load	Coefficients	Weight (kg) of baggage per passenger	Fuselage types: Round	Double bulb	Large-dimensioned round
Containerless	K_{br} (baggage compartment reserve)	q_b 15	—	—	2.7—2.9
		q_b 20	1.2	1.4	2.9—3.1
Containerless	Baggage density γ kg/m^3	—	120	120	130
Containerized	K_{br} (baggage compartment reserve)	q_b=15	—	—	1.9—2.5
		q_b=20	—	1.5	2.0—2.8
Containerized	Baggage density γ kg/m^3	—	230—250		300—310
Cargo density γ kg/m^3		—	290—300		
Coefficient of usage (K_{use})			0.63	0.585	0.44
Coefficient of arrangement density (K_{ad})			1.2		1.35
Statistical coefficient (ψ)			1.0	1.2	1.05
Coefficient of section form (a_f)			1.0	1.06	1.0

Airbuses and giant airplanes (of the Boeing 747 type) in an economic relationship are located on a new higher level, not only as the result of a high commercial payload (Fig. 2.17), but also

due to a significantly larger cargo compartment volume. The latter increases their productivity and, consequently, reduces operating expenses. It is possible to form an impression of the dimensions of the compartments for storing cargoes on the Boeing 747 if, for instance, we recall that it reaches 60% of the cargo compartment volume of the DC-8F, which was intended totally for cargo shipments. The economic effect of large baggage and cargo compartments allows, firstly, improvement of the load capacity characteristic in the passenger variation, which is "limited by volume" (see Fig. 2.16), and secondly, it allows a significant increase in maximum weight in the cargo-passenger and cargo variations (thus, the Boeing 747 in the cargo variation can transport up to 100 t of cargo). We recall that limitations of loads by condition of space are either connected with a higher class of seat arrangement (mixed variations) or arise on flights with an underfill of passengers.

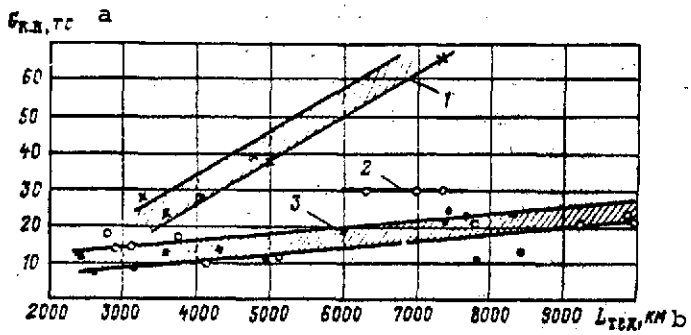

Fig. 2.17. Commercial payload of airbuses (1), airplanes with stretched fuselages (2), and airplanes of the first two generations (3): x - airuses; o - modifications; • - initial variation.

Key; a. G_{cp}, t; b. L_{tech}, km

The significant increase in tonnage of the airbus (with a short flight range) will lead to an increase in the weight of the fitted airplane. However, the amount of its weight attributed to a unit of the commercial payload weight (Fig. 2.18) the same as that for the maximum number of passengers, does not increase. This is highly essential, since the effect of weight is so great. For instance, a decrease in design weight and fuel by 10% with a corresponding increase in commercial payload is in an economic relationship equivalent to a decrease in the initial cost of the design and the engines by 50%. /123

Concerning aerodynamics, "after some relative lag in its development during the 1950's, a noticeable expansion is presently being observed in aerodynamic investigations, connected with, for instance, detailed study of the flow-past stream. These investigations are highly productive and allow the decrease in aerodynamic resistance of new airplanes by 15% to be foreseen."[2.6] For airbuses

[26] In order to assert how significant this is, it can be compared with the results of retaining boundary layer laminarity on all load-bearing surfaces, which is evaluated (in the case this possibility appears) as a 30% decrease in resistance (flight, No. 3085, 1968, p. 612).

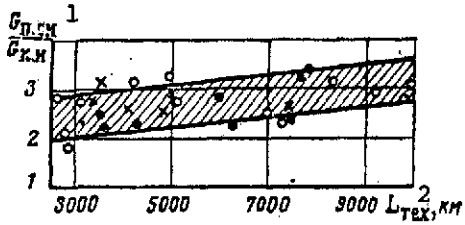

Fig. 2.18. Weight of a fitted airplane per unit of commercial payload of airbuses (x), initial variations (•) and modifications (o) of airplanes of the first generations.

Key: 1. G_{ef}/G_{cp}; 2. L_{tech}, km

on short and medium routes, this is equivalent to a decrease in direct expenses by 3%. Localized aerodynamics of airplanes have begun to acquire great meaning and a significant effect is achieved through their improvement.

Another factor which promotes an increase in economic effectiveness is expansion of the spread of flight ranges, within the limits of which operation is practically equally economic. It was noted above that the high number of types in the fleet leads to its greater expense and makes operation more difficult. At the same time, using airplanes on flights which are significantly shorter than those for which they were created and thereby shortening the average length of flights also deteriorates the economy of the tranport system. The escape from this contradiction was at first found by means of creating airplanes in two variations -- with a short and long fuselage, expanding the possibility for their rational use on routes with essentially different lengths. After that designers turned to a search for a new type of airplane, which differed both in overall dimensions and in its wide spread of flight ranges.

Finally, the problem of repairability, which acquired significant reality in planning. The fact of the matter is that the time for nonproductive labors spent on disassembly and assembly of equipment reaches 60-70% of the total required time. This explains the attempt to decrease it. /124

In this way, high commercial returns and load capacity (with an underfill of passengers), high aerodynamic properties and flight speed, low specific fuel consumption and increased repairability, a decrease in expenses on technical servicing and delays in takeoff will show a favorable effect on economic effectiveness and will lead to a decrease in operating costs. Besides this, airbuses possess the economic potential (according to an increase in thrust and space reserves), which can lead to a further increase in productivity and a decrease in the cost of fares.

The profitability of air transport in the first years of operation of airbuses will apparently not increase as the result of the high cost of their introduction and the initial disparity between the available space (according to number of seats and cargo compartments) and volume of shipments. Correspondence in this will approach along with a growth in the fleet over 2-3 years after introduction of airbuses into operation. It is projected that the limiting increase in volume over this period will attain a value of

30-32% and airbuses will overtake their predecessors in profitability.

8.2. Flight safety. The success and circulation of modern passenger airplanes depend to an immense degree on technical improvements intended for the achievement not only of economic effectiveness but also of maximum reliability and safety in flights. Over the course of the two previous decades, a steady tendency has been observed toward a decrease in the number of accident occurring per 100 million airplane kilometers (Fig. 2.19, a) and the number /125 of casualties per 100 million passenger kilometers (Fig. 2.19, b). The number of accidents, which increased during the 1950's was caused by an increase in airplane dimensions. This situation brought about apprehension over a future direction connected with a sharp increase in the passenger seating capacity of airbuses. A more exacting study led to reassuring forecasts. It is clear, naturally, that a future increase in airplane dimensions will require an even greater increase in norms (or standards) of safety. At the same time, an increase in air communications safety must be achieved without economic losses, inasmuch as in the past many technical improvements simultaneously accompanied both increased flight safety and increased economic effectiveness.

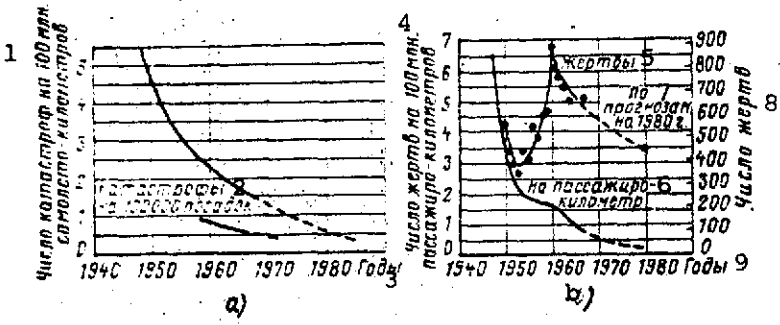

Fig. 2.19. Increase in flight safety (a) and decrease in the number of casualties (b) on regular air routes. According to data of work [71].

Key: 1. Number of accident per 100 million airplane-kilometers; 2. accidents per 100,000 landings; 3. years; 4. number of casualties per 100 million passenger kilometers; 5. casualties; 6. per passenger-kilometer; 7. according to forecasts for 1980; 8. number of casualties; 9. years.

The systems for providing safety in flights are a combination of devices whose purpose consists of preventing flying emergencies during the course of the entire operating period of the airplane. The development of these systems was based on determination of the probable causes for flying emergencies and on analysis of the results of their investigation. Corresponding recommendations for their prevention were worked out simultaneously.

The probability of failures can be determined during the planning process with mathematical equipment.

Increasing flight safety up to the required level is achieved with definite principles of airplane planning and

improvement of the transport system as a whole. The planning principles include: creation of constructions which are safe during destruction, duplication and reserving of components in equipment systems and many others.

Providing flight safety on transport depends on the work of all personnel, beginning with the dispatcher and weather service and ending with the flight crew, its preparation and training. It also depends on the organizational principles for solving problems in the transport system and on methods of technical servicing (repair and adjusting operations, preparation for flight and so forth). There is, naturally, a definite interconnection between these two positions. Designers, developing projects, can essentially effect the prevention of mistakes in pilotage and servicing through, for instance, creating good pilotage characteristics for the airplane, reduced crew fatigue, convenient accesses for inspection during technical servicing, etc., in a word, providing simplicity in pilotage and operation.

In presenting brief information on the situation and tendencies in one of the most important areas in passenger aviation theory and practice, we can recall that questions of safety are closely tied to reliability in the airplane construction, power layout and equipment systems, which are examined in more detail in the eighth part of this work.

PART 3. PROBLEMS IN WEIGHT AND DIMENSIONS OF PASSENGER AIRPLANES /126

Chapter 9. Weight Effectiveness of Airplanes

9.1. Meaning of the problem. Weight and dimensions, the basis for planning and design of all engineering constructions, acquire the most significance in aviation. High effectiveness in a passenger airplane is achieved primarily through the decrease in the weight of the construction, power unit, equipment system, and also through high density in its arrangement, i.e. maximum space utilization. Weight problems must therefore be included among the major problems of planning. Experience in the creation of modern aircraft allows us to speak of their significant increases and on the appearance, in turn, of the "weight barrier," whose break through is a real task. It does not follow from this that any sort of limits arise in the course of further development. In the past, true, attempts were made to found the possibility for their appearance. It was asserted, for instance, that the limit exists in increasing airplane dimensions, which was to emanate from the "square-cube" law. Development history has shown the unsoundness of similar assertions. The "weight barrier" concept, however, as will be shown below, is at the same time correct. It is not identical to the "limit" as a whole, but only to the limit at a definite stage in an area of definite values for parameters which can be overcome through qualitative changes.

Of the total number of technical and economic problems which at the present time are determining ones, the weight problem is isolated, especially during creation of high-tonnage airplanes (weighing 150-350 t). However, the meaning of this problem increased not only as a result of the appearance of hindrances to a further decrease in the relative weight of the airframe, but also in connection with the ever more widespread usage of method of optimization based on criteria which are weight and economics. The special attention directed to problems of weight is also explained by the fact that overweighting an airplane is an unavoidable reason for nonfulfillment of the basic flying characteristics. It was exactly because of this that everyone recognized that the major and /127
most complex problem in the creation of a modern airplane is the requirement to refrain from increasing the initial value for the weight of the fitted airplane, on the basis of which all its projected characteristics were formulated.

The complexity of the weight problem is connected with the necessity for achieving as high a load capacity and productivity as possible. The required result is, generally speaking, achieved by increasing aerodynamic qualities, flight speed, engine efficiency and weight effectiveness. However, firms planning the high-tonnage ships came to approximately the same conclusion which was published in "Flight" (from 19 December and 17 October, 1968) and which supports that stated above. In connection with the creation of the

Boeing 747 airplane, the magazine wrote: "The problem of weight became one of the fundamental problems," which for a long time "threatened the planning of this airplane."

The basic characteristic of an airplane (load capacity as a function of range) and its economy can be maintained, true, even in the case of some overweighting of the construction by means of increasing the takeoff weight and raising the load capacity commensurately. With this, the takeoff weight must be increased to a high value for the purpose of maintaining not only the weight effectiveness, but also the economic effectiveness:

$$\Delta G_0 = \Delta G_{ef} + \Delta G_{cp} + \Delta G_f, \qquad (3.1)$$

where ΔG_{ef} -- the increase in weight of the empty fitted airplane; ΔG_{cp} -- increase in weight of the commercial payload for compensation of ΔG_{ef} so as to retain economy; ΔG_f -- increase in the weight of fuel to maintain range.

An increase in the airplane's takeoff weight and a corresponding increase in strength is utilized (or provided) as a reserve course in a case where possible deviations from the weight program during the process of planning cannot be successfully eliminated. In the absence of reserves in thrust, takeoff and landing characteristics will be sacrificed. It should be noted that on transport airplanes a similar solution is prevented by stricter conditions for their operating bases. Therefore, the weight problem in planning these types of airplanes acquires even greater acuity. This position was reflected, for instance, by communications appearing in the foreign press during the creation period of the C-5A airplane. It was stated in one of them that during the first period of development, "the weight of the airplane was a factor which caused significant disquiet in the Lockheed firm and the government" and only exclusive measures taken in a wide plane and over a period of many months allowed passage of the weight program and this was under such conditions that only the tenth airplane had the guaranteed empty airplane weight. /128

In the process of aviation development, it occurred that speed data and many others such as comfort level, degree of space utilization in various passenger airplanes of the same class (and the same technical level) were close together. The small number of characteristics in which they differed includes the weight characteristic, regardless of the fact (or perhaps because of it) that to a greater degree it determines the economy of a passenger airplane. Weight perfection is usually known in a comparison (there are also, understandably, other ways). However, equal sized airplanes which are used to a higher degree for comparative evaluation according to absolute weight characteristics are generally speaking few. In the majority of cases, the geometric dimensions, layout and arrangement

of airplanes do not coincide and this eliminates the possibility for clarifying their weight effectiveness (i.e. properties which are usually called construction likeness) by means of the simple comparison of absolute (or relative) weight data. Evaluation of these properties in full measure is possible only with consideration for determining conditions, which first of all include: the known law for change in the load ratio according to airplane tonnage, comparable flight productivity (the product of cargo weight and flight range) and a number of other factors.

9.2. Load ratio of airbuses. The weight problem during planning of large-dimensioned airplanes (including airbuses) has begun to bother designers to a significantly greater degree than during development of airplanes of previous generations. This is in part connected with a decrease in the load ratio of airbuses, the explanation for which is still disputed. We recall that a constant increase in load ratio with an increase in airplane dimensions (tonnage) was observed earlier (Fig. 3.1). It occurred regardless of the action of the so-called "square-cube" law and regardless of the increase in flight speed and the higher requirements for safety, reliability, technical servicing and comfort. With this, its increase was a result of a number of reasons, which include: an increase in specific load on the wing, a decrease (with an increase in tonnage) in the power-to-weight ratio (which was promoted by an increase in the number of engines and an increase in available runway length for airplanes with long flight ranges), an increase in the relative fuel reserve with a decrease in the relative weight of commercial payload, a decrease in specific engine weight and relative weight of the equipment and so forth. (In a word, the takeoff weight in a functional dependency of the load ratio on the airplane's tonnage is a generalizing parameter.) For airbuses, some of these favorable reasons disappeared and the value of the total load ratio decreased sharply. This is supported by a graph (see Fig. 3.1) on which the curves defining the dispersion zones for the points indicating total load ratio ($\overline{G}_{tl}$) for airbuses proves to be lower, and the commercial return ($\overline{G}_{cp}$) is higher than with their predecessors. The latter corresponds to the best of the modifications. /129

For airplanes of previous generations, which are equal to airbuses in tonnage, a four-engine configuration and a relatively slight increase in fuselage diameter are typical. The significantly higher range of their flight (abc and ade in Fig. 3.2) led to a higher load ratio as a function of fuel and a lower commercial return (see Fig. 3.1). Or vice versa, with the same values for load ratio and flight range, the tonnage of the airplane was significantly lower (see Figs. 3.1 and 3.2).

The reason for the low level of weight return in airbuses (see Fig. 3.1) with a simultaneous increase in productivity can be found in the following: in the significant increase in fuselage cross section, which led to a decrease in the degree of utilization /130

of its space; in a sharp increase in passenger seating capacity and commercial payload; in a sharp increase in the weight of the airplane without fuel (Fig. 3.3) and the takeoff weight (see Fig. 3.2) with a comparable flight range, which leads to an increase in required strength in flight and in landing; in a decrease in the relative weight of fuel with the same range (due to the low specific fuel consumption with engines having a high degree of by-pass), which decreases wing loading; in the use of the two- and three-engine configurations for airbuses.

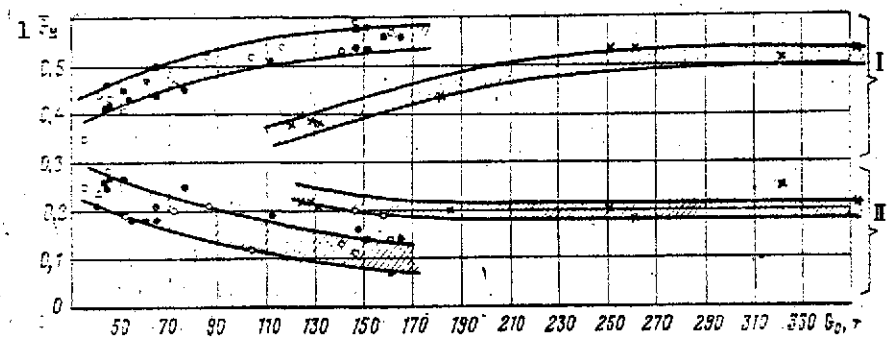

Fig. 3.1. Dependency of the total $\overline{G}_{tl}$ (I) and the commercial $\overline{G}_{cp}$ (II) load ratio of operation jet airplanes (•), their modifications (o) and wide-fuselage airplanes (x) on the takeoff weight.

Key: 1. $\overline{G}_{\ell}$

With a more detailed examination of these reasons, it is easy to show that the increase in dimensions and weight of the fuselage occurs not only as the result of a sharp increase in passenger seating capacity, but it is also connected with a decrease in the degree of space utilization in relation to passenger loading. This is explained by the appearance of a second aisle, an increase in the height of lounges and the creation of large reserves in baggage and cargo compartment volumes for an increase in shipment of cargo simultaneously with passenger shipments. We recall that with a diameter of up to 4 m, the fuselage dimensions were selected from conditions of G_{cp} = max. With diameter limited to 6 m, its dimensions allow the commercial payload weight to be shifted to 30-50% greater than the maximum weight (see Fig. 2.3). The reserves are used for shipping cargoes on flights with an underfill of passengers, but for the main load, the fuselage turns out to be redimensioned, which is reflected on the weight balance of the airplane. For instance, the dependency of the relative weight of the fuselage ($\overline{G}_f$) on takeoff weight (G_o) is rather strict for jet airplanes of the first two generations, and does not now corresond to the large-dimensioned fuselages (Fig. 3.4). The reason for this can easily /131

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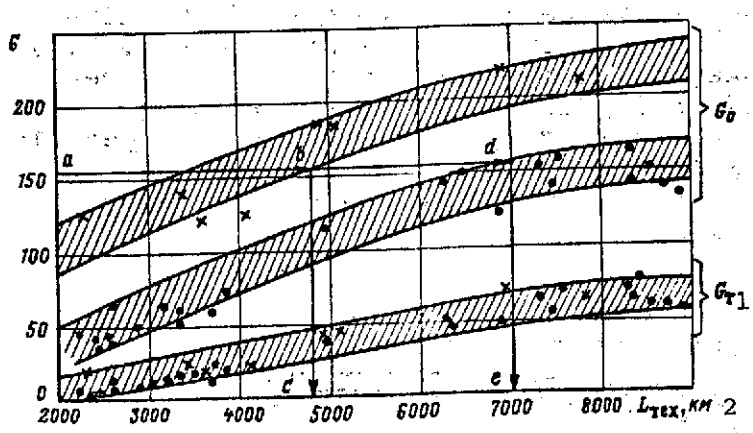

Fig. 3.2. Takeoff weight G_0 and fuel reserve G_f of operational airplanes (•) and airbuses (x) with different flight ranges.

Key: 1. G_f; 2. Ltech, km

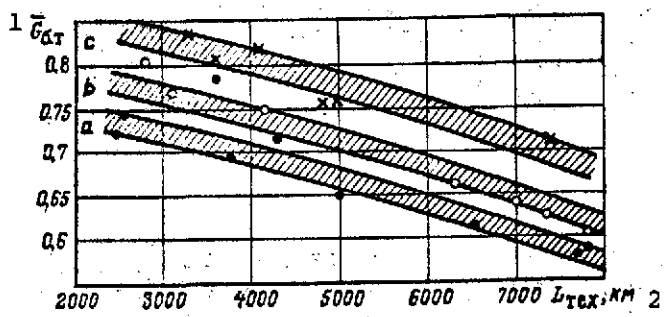

Fig. 3.3. Relative weight of an airplane without fuel: a - initial variations; b - modifications; c - airbuses.

Key: 1. $\bar{G}_{w/of}$; 2. Ltech, km

be understood from examining the following equation: $\bar{G}_f = f(G_0) = f(G_{ef} + G_{cp} + G_f)$.

The presence of a similar dependency for many airplanes (besides airbuses) can explained by observing the earlier relationship between the increase in takeoff weight and the increase in commercial payload (G_{cp}) and, consequently, the increase in fuselage dimensions. It is necessary to emphasize that the weight of the latter depends on airplane tonnage only with the presence of this relationship[1]. If takeoff weight is increased (so as to increase range) with an increase or retention of the area of the wing or empennage but commercial payload is retained, the weight of the fuselage is changed insignificantly. And, conversely, with an increase in G_{cp} with G_0 = const, fuselage weight increased sharply. This is also characteristic for airbuses, in which a redistribution of the fuel weight (G_f) and the weight of the commercial payload (with a comparable value for takeoff weight) occurred, and the relative weight of the fuselage increased as a result of its re-sizing and increased required strength. The authors of some works are disposed to explain the drop in load ratio for airbuses with only the increase in fuselage weight. It is difficult to agree with this unconditionally. This is more likely to be the result of a combination of a number of reasons, and the redistribution of the relative weights in the total weight balance of the airplane (in particular,

[1] The dependency $q_f = f(G_0)$ is sometimes used without considering this condition.

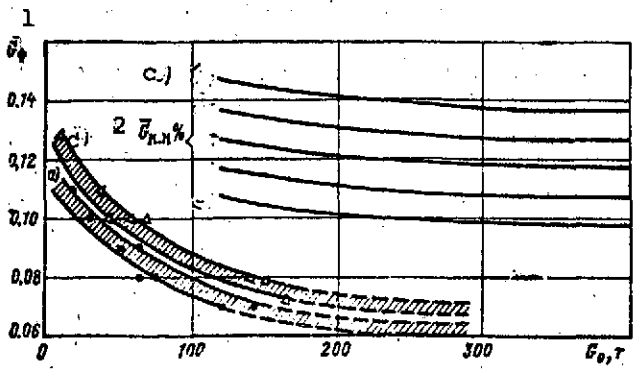

Fig. 3.4. Change in the relative weight of operational airplane fuselages with engines on the wing (a) and on the fuselage (b) as well as airbuses (c) in dependency on the takeoff weight and commercial load ratio ($\bar{G}_{cp}$ %).

Key: 1. $\bar{G}_f$; 2. $\bar{G}_{cp}$ %

the increase in relative weight of the commercial payload and fuselage by 50-70%) is one of these.

The effect of the two latter reasons on the weight of the fitted airplane and the load ratio are examined in detail in Section 9.5. It should be stated here that the weight of the fitted airplane is determined primarily by the commercial payload and conditions for takeoff, landing and flight level. These data determine the fuselage, wing area and thrust of the engines. /132

The reason listed before the last one in the above is no less serious. The fact of the matter is that for development of passenger and transport airplanes, increase in their tonnage with a simultaneous increase in range and flight speed is typical, especially with the transfer to new types of power units. Both led to an increase in fuel reserve. Therefore, airplanes which correspond to airbuses in tonnage and speed had a significantly larger fuel reserve (see Fig. 3.2) and a lower commercial payload weight. With their total retained, redistribution in weight toward an increase in the latter will lead to a decrease in the total load ratio, since the construction weight increases. Fig. 3.5, which reflects the drop in total load ratio with an increase in commercial return which is characteristic for airbuses serves as an illustration of this. The straight line (b) on this graph shows the limiting relationship of these parameters. It represents a line of equal values, i.e. $\bar{G}_{t1} = \bar{G}_{cp}$. Actual values may turn out on this graph only for airplanes with atomic engines, whose fuel weight is practically approximating zero.

The weight of the power unit increases as the result of the latter of the listed reasons, since the weight of two or three engines with a thrust selected from conditions of an equal degree of safety upon failure of one of the engines during takeoff is greater than the weight of four engines. True, the appearance of engines with a high degree of by-pass eases this condition, although a constant decrease in specific weight was also observed earlier (see Fig. 1.11). We recall that a decrease in the number of such engines does not decrease airplane economy. /133

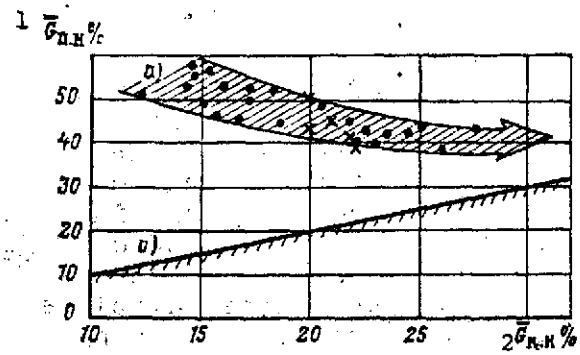

Fig. 3.5. Decrease in total load ratio according to the increase in commercial load ratio (a) and a limiting value for the first of these (b). Operational airplanes (●), airbuses (x).

Key: 1. $\bar{G}_{tl}$ %; 2. $\bar{G}_{cp}$ %

Both the fact of a decrease in the total load ratio of airbuses and the character of the curve describing the change in its value according to airplane tonnage (see Fig. 3.1) are interesting. The curves in the upper zone (I) show that the increase is sharper at first, and then slowed down. The curves in the lower zone (I) have a section of stabilization and even some decrease, which is connected with the appearance of the "weight barrier" which is examined in Chapter 11.

9.3. Weight effectiveness criteria. Analysis of the effectiveness of airbuses in comparison with operational airplanes, which can be conducted with a group of criteria represents interest. The load ratio, generally speaking, can serve as a single-value criterion of effectiveness only with strict fulfillment of comparison conditions, for instance, in comparative evaluation of equal-sized airplanes with approximately the same flight range, with the same power unit configuration, with engines on a single technical level and so forth. The latter condition, which usually slips from view, has great significance. Thus, a decrease in the fuel consumption per kilometer will lead to a decrease in the total load ratio to a greater degree than will a decrease in takeoff weight for other reasons[2]. With this, we recall that of all the types of load ratios, the most effective criterion is the commercial load ratio, since an increase in fuel reserve with low aerodynamic qualities or a high specific consumption will lead to an increasein total load ratio without an increase in productivity. True, the commercial return also depends to some degree on the fuel reserve which is considered in the takeoff weight.

Incidentally, the major of the engine weight effectiveness criteria, i.e. its specific weight ($\gamma = G_e/R$), also cannot now be used without considering an additional factor -- the drop in thrust according to speed $R = f(M)$. This drop achieves a significant value with an increase in the degree of by-pass. /134

[2] Parametric analysis on the basis of a group (or system) of criteria was proposed by Ye. A. Ovrutskiy [40] and received widespread development in works [62] and [92].

consequently, this criterion also, like the airplane's load ratio, does not fully determine the weight perfection of modern equipment.

Criteria of effectiveness which connect weight characteristics and productivity of the airplane are now frequently being used [62, 76, 91]. In the first of these works, a parameter of effectiveness $A_a = \frac{G_{ef}}{G_{cp}L}$ ($\frac{kg}{t \cdot km}$) is recommended. In the two latter ones, the mathematically reversed value is recommended, which is proposed to be called the index of effectiveness [76] or the specific productivity [91]. The statistical curve (Fig. 3.6), constructed according to data on a large number of airplanes and airbuses, expresses the conformity of change in parameter A_a according to flight range. Strictly speaking, this parameter will lead to an evaluation of not only weight effectiveness. Considering (through flight range) the aerodynamic properties of the airplane and economy of the engines, it allows overall perfection of the airplane to be judged, i.e. it is one of the parameters of transport effectiveness [72].

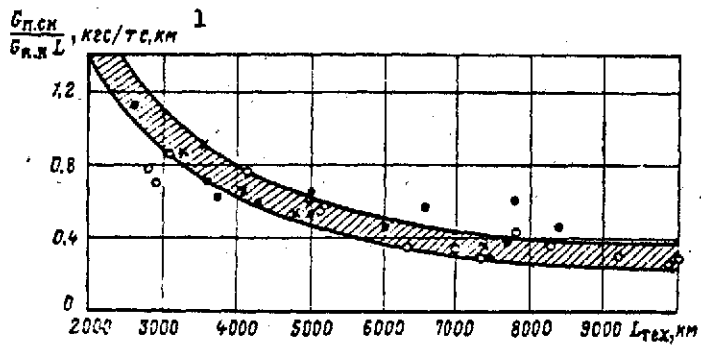

Fig. 3.6. Parameter of transport effectiveness for operational airplanes (•), their modifications (o) and airbuses (x).

Key: 1. $G_{ef}/G_{cp}L$, kg/t.km; 2. L_{tech}, km

The relationship of the weight of the fitted airplane to the maximum number of passengers (Fig. 3.7) can be used as a parameter of weight effectiveness with sufficient approximation. The necessary condition for comparative analysis in this case is equal spacing between rows of seats for all airplanes. Airplanes of various classes with typical, stretched and wide fuselages form two relatively compact /135 zones on the graph. In the upper parts of each of them are basically located points corresponding to the initial variations of the airplanes, and in the lower parts are their modifications. The similarity supports reliability of the dependence. This parameter can to a known degree also characterize economic effectiveness, since it is similar to the parameter expressing the relationship of airplane cost to the number of passengers. (It is also known that cost is proportional to the weight of the fitted airplane.)

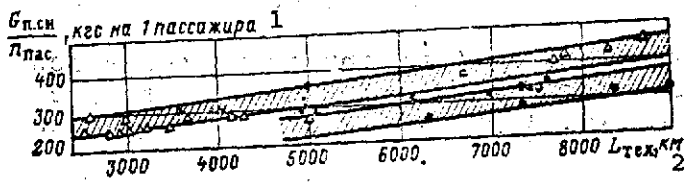

Fig. 3.7. Weight of an empty fitted airplane, related to the number of passengers. Airplane with engines on the fuselage (Δ) and on the wing (o); airbuses (x).

Key: 1. G_{ef}/n_{pax}, kilogram per passenger; 2. Ltech, km

Evaluation of the weight perfection of the construction is also allowed by the parameter connecting weight of the fitted airplane with its dimensions, which can be called the "weight quality" of the airplane. The regularity of its change is presented in Fig. 3.8. In its construction, the area of the lateral surfaces of the pods was ignored.

$$q_{S\ wet} = \frac{G_{ef}}{S_{wet}} = \frac{G_{ef}}{2(S + S_{em}) + S_f} \text{ kg/m}^2 \qquad (3.2)$$

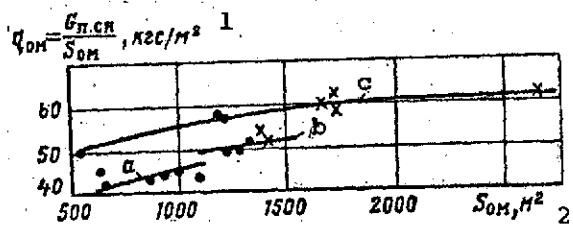

FIg. 3.8. Specific weight of a fitted airplane ($q_{S\ wet}$) according to area of the wetted surface (S_{wet}) with a specific wing loading (p), lying within limits of: a - 350-480; b - 490-530 and c - 560-660 kg/m^2; o - operational airplanes; x - airbuses.

Key: 1. $q_{wet} = G_{ef}/S_{wet}$, kg/m^2; 2. S_{wet}, m^2

Weight effectiveness is achieved, strictly speaking, as the result of creating three composite parts of an airplane which are perfected in a weight relationship: the airframe construction (G_{af}), the power unit (G_{pu}) and the equipment systems (G_{eq}). Therefore, criteria allowing judgment of each of these to be made separately are necessary. For the power unit as a whole, the dependence of its relative weight on the power-to-weight ratio of the airplane can be used (see Fig. 3.16). For the airframe construction, the criteria may be the values: /136

$$G_{ef} = \frac{G_{cp}}{G_{af}} \text{ or } G_{ef} = \frac{G_{cp} + G_{pu} + G_{eq}}{G_{af}}, \qquad (3.3)$$

which can be called the effective load ratio of the structure. Physically, these parameters represent the load-bearing (in a strength relationship) capability of the airframe construction (G_{af})

or the degree of its loading. They are more objective, since they take into account only the weight of the construction without the effect of the fuel reserve and the weight of equipment [64].

The effective load ratio (G_{cp}/G_{af}) for many turbojet airplanes lies within the limits 0.65±0.05. It is interesting that in airplanes with turboprop engines weighing 30-80 t, it comprised 0.92±0.06. Such a significant difference can be explained by the lower weight of the unswept and relatively thick wing, which was loaded over the course of the entire flight with a heavier power unit, and also a lighter fuselage with a lower differential in internal pressure, and, finally, the absence of sweep in the tail empennage and a more advantageous layout for its arrangement. Transport airplanes with jet engines, swept wings and a T-shaped empennage have just as high a value for the effective load ratio, 0.86±0.06. In this case, the explanation can be sought in the significantly higher degree of fuselage space utilization and higher strength characteristics of the material for its construction. It should be kept in mind that the upper limits for the values presented are achieved on airplanes with high tonnage.

For analogy with the parameter of weight quality of a fitted airplane qS_{wet}, it is possible also to examine the weight of the airframe construction as it relates to its surface. During examination of the fitted airplane, it is possible to use a parameter similar to the parameter for the effective load ratio of the airframe. It also lies in a narrow range and comprises 0.35±0.05 for turbojet passenger airplanes.

The relative weight of the airframe ($\bar{G}_{af} = G_{af}/G_0$) is also used for evaluation of effectiveness, but the criterion (A_{af}) connected with productivity is recommended. In work [76] it is proposed that hourly productivity ($G_{cp} \cdot V$) be examined during this, but in work [62] it was shown that preference should be given to flight productivity ($G_{cp} \cdot L$):

$$A_{af} = \frac{G_{af}}{G_{cp}L} \text{ kg/t·km} \quad \text{or} \quad A'_{af} = \frac{G_{af}}{G_{cp}V} \text{ kg/t·km/h.} \qquad (3.4)$$

It is possible to say the same thing about the parameter presented as about the total load ratio and the parameter of transport effectiveness (A_a). Some of them to a greater, and some to a lesser degree depend on specific fuel consumption and the aerodynamic quality. This can also serve to explain the tendency for the further decrease in the value of (A_{af}) in cases where the relative weight of the airframe ($\bar{G}_{af}$) stabilizes or even increases. /137

In conclusion, it is interesting the examine the data (Fig. 3.9) and draw some conclusions from the analysis presented here.

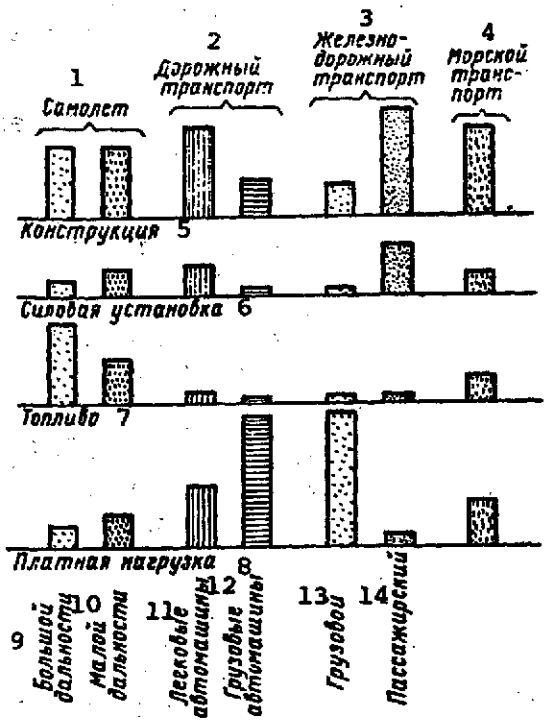

Fig. 3.9. Weight relationship of various transport means (in % of total weight).

Key: 1. Airplane; 2. Road transport; 3. Railroad transport; 4. Marine transport; 5. Construction; 6. Power unit; 7. Fuel; 8. Payload; 9. Long range; 10. Short range; 11. Automobiles; 12. Trucks; 13. Freight; 14. Passenger

The effectiveness of the airframe construction, just as that of the fitted airplane can be determined in the best way with a group or system of criteria. It is understandable that comparison of the weight, as any other effectiveness, is most desirably conducted according to a single index, which would characterize the effect of geometric and other parameters of the airplane and engines together into weight effectiveness. However, the task of formulating a single index for technical perfection is extremely complex and has not yet been solved. At the same time, the modern theory for optimum planning does not know the correction means for solving problems in the presence of many criteria. Therefore, the recommended multicriterial evaluation is used for qualitative parametric analysis for the most part because it possesses many advantages. In particular, if the extreme is not discovered according to one criteria, it may be according to another. in similar analyses, special attention is paid to the formulation of a system of criteria and to checking them according to data from actual airplanes. Without preliminary solution of this problem, it is difficult to gain confidence in the results. /138

Parameters which functionally depend on the takeoff weight of the airplane, such as the load ratio, relative weight of the fuselage, wing and so forth, cannot be used in the comparative evaluation of weight effectiveness of airbuses with airplanes from previous generations. The reason for this, as was already noted, is the redistribution of relative weights in the overall weight balance of the airplane. Parameters of weight effectiveness connecting the weight of parts of the airplane with its dimensions, commercial payload or number of passengers, as well as with productivity, also remain true in application to airbuses, since progress

in the area of aviation equipment has allowed the satisfactory relationship to be achieved between the fuel consumed over the course of the flight and flight speed on one hand and the weight of the empty fitted airplane and commercial payload on the other hand.

An analysis conducted using these parameters shows that the weight effectiveness of airbuses is practically maintained on the level of airplanes from previous generations. It is understandable that for a further increase in economy, the retention of this level is not sufficient. For its planned increase, the weight of the construction is still great, and measures are required for its reduction. Concerning the drop in total load ratio of airbuses, this is their peculiarity. And on the other hand, it shows the limitation of load ratio as a criteria of effectiveness. The latter supports an increase in productivity and commercial load ratio.

9.4. Coefficient of takeoff weight rise. Methods for creation of light constructions are impossible to investigate without considering the coefficient of rise (ϕr_0). We recall that this concept represents the measure of takeoff weight change with weighting or lightening elements of construction or equipment (ΔG_i) and is defined as

$$\phi r_0 = \frac{G_0 \pm G_{0\ in}}{\Delta G_i}, \qquad (3.5)$$

where $G_{0\ in}$ and G_0 are the takeoff weight of the airplane before and after the change.

The coefficient of rise presupposes maintenance of all flying and strength characteristics, which is fulfilled through maintaining the relative fuel reserve ($\bar{G}_f$ = const), the specific wing loading (p = const) and the power-to-weight ratio of the airplane with consideration for a completed takeoff or aborted landing upon failure of one of the engines ($\bar{R}_{n-1}$ = const). Consequently, the conditions of retaining the flying characteristics while changing the weight of one of the components (ΔG_i) will lead to an increase in dimensions and weight of the wing and empennage, fuselage weight, power unit thrust and fuel reserve. Furthermore, the change will occur not only by the value of ΔG_i, but to a significantly larger degree, since an increase in the weight of all the listed parts of the airplane and fuel are considered. The size of the coefficient of rise for passenger airplanes is located within limits of from 2 to 5, depending on the fuel reserve. The upper limit corresponds to the load ratio as a function of fuel, which is equal to 50%. Eq. (3.5) is the mathematical expression of the coefficient of rise concept itself. It can be computed by calculating formulas (3.6), (3.7) or (3.8), which were proposed by V. M. Sheynin [62],

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A. A. Badyagin [4] and V. I. Kozlovskiy [27]. The latter of these is the simplest, although it will lead only to an approximate solution. All formula are interesting from the point of view of the authors' approaches to solution of this problem.

The formulas mentioned for determining the coefficient of takeoff weight rise has the appearance

$$\varphi_{r_0} = \frac{1}{\Delta\bar{G}_i}\left\{\frac{\bar{G}_{cp}+\bar{G}_i+\Delta\bar{G}_i}{1-(\bar{G}_{c.af}+\bar{G}_{pu}+\bar{G}_{eq.f}+\bar{G}_f-\bar{G}_i)}-1\right\}; \quad (3.6)$$

$$\varphi_{r_0} = \frac{1}{1-\bar{G}_r-\frac{\partial G_{ef}}{\partial G_0}}; \quad (3.7)$$

$$\varphi_{r_0} = \frac{1}{0{,}7-\bar{G}_f}, \quad (3.8)$$

where $\bar{G}_{cp}$; $\bar{G}_{c.af}$; $\bar{G}_{pu}$; $\bar{G}_{eq.f}$; $\bar{G}_f$; $\bar{G}_i$ -- relative weight of the commercial payload, airframe construction, power unit, equipment, fittings and controls, fuel and that part of the airplane whose weight changes; $\bar{G}_{ef}$ -- weight of the empty fitted airplane.

The area of usage for these formulas is limited to planning stages.

The equation for ϕ_r is true under conditions of maintaining $\bar{G}_f$ = const. If conditions of the airplane's crew with an increased wing area (as a result of increasing airplane weight) allows a decrease in $\bar{G}_f$, the values of ϕ_r will be somewhat lower than those determined by the equation.

9.5. The effect of a change in takeoff weight on the weight of the fitted airplane. Investigation of this problem has acquired special interest with the creation of wide-fuselage airplanes. During the process of work-up and the future development of the project, during planning of modifications of short-range or long-range airplanes (with an increase in G_{cp} or G_f respectively), takeoff weight, as a rule, increases. With this, it is understandable that the weight of the fitted airplane increases, but each time to a different degree. The degree of effect which G_{cp} and G_f have on the weight of the fitted airplane is also determined during a comparative evaluation (by means of comparison) of airplanes having approximately equal passenger seating capacity but different flight ranges or vice-versa. /140

The effect of increased takeoff weight on the weight of the empty fitted airplane (G_{ef}) are extremely different in different cases. It depends: a) on the reason for its increase (an increase in fuel reserve or weight of commercial payload); and b) on requirements outlined during this for takeoff and landing characteristics and flight altitude. If these characteristics must be maintained, and with an increase in takeoff weight, the weight of the

fitted airplane will increase significantly[3], since it will be necessary to increase the wing area and thrust of the engines.

If the listed characteristics can be successfully changed in a precise relationship with the rise in takeoff weight, the weight of the fitted airplane will increase only in a case where the commercial payload and, as a result, the dimensions of the fuselage are increased. With this, the calculated landing weight and the weight of the airplane without fuel are increased, which will lead to an increase in required strength and weight of the wing and landing gear. When the reason for increasing takeoff weight is an increase in fuel reserve, the weight of the fitted airplane is changed to a significantly smaller degree.

All the positions examined are relatively evident. One of them, apparently, needs clarification. This is a case in which the takeoff weight increases as the result of an increase fuel reserve without the condition of maintaining the takeoff and landing characteristics. In this case, the weight of the airplane without fuel and the calculated landing weight are changed insignificantly. Therefore, the strength of the wing and landing gear are as a rule not increased on the basic calculated case, and their weight is practically maintained. Only the weight of the wheels is increased, if they were selected without reserving. Loads on the tail empennage (in connection with the increased specific loading on the wing) increase somewhat, but the relative amount of their increase is insignificant. The weight of the fuselage is practically unchanged with an increase in takeoff weight in this case. With an increase in the latter, the loads on the fuselage increase only slightly from the increase in loads on the tail empennage. However, their share in the total flexion moment usually does not exceed 22-24%, and this moment acts only on the longitudinal members of the tail portion of the fuselage, whose weight comprises 15-17% of the total weight of the fuselage. From this, the insignificance of the increase in the fuselage weight is fully evident, even if the loads mentioned increase noticeably. Its weight is not, however, great even in cases in which the takeoff weight is increased by 10-15%. The weight of the fitted airplane in the sum of the weight changes in all of its parts is increased no more than by 0.2-0.3% of the takeoff weight. Consequently, with an equal increase in the amount of commercial payload or fuel, the weight of the construction in the first case increases significantly to a larger degree than with an increase in fuel. The same is true for a case in which the takeoff and landing characteristics and flight level are kept unchanged. /141

In this position on fuselage weight, it is possible to discern a definite contradiction in the known formulas [62] and the graphic dependencies in which fuselage weight is expressed as a function of

[3] The amount of this increase also simultaneously depends on the first condition, i.e. on the reason for the increase in takeoff weight.

takeoff weight. It should be noted that the area of change in similar formulas and dependencies has limitations and that they are not applicable to airbuses. These formulas were true up to such time as the commercial payload (on which fuselage weight primarily depends) and fuselage dimensions increase in a definite dependency on the rise in takeoff weight. With the appearance of wide-dimension fuselages, this dependency was destroyed.

Chapter 10. Methods of Creating Light Construction

10.1. Problems of weight planning. In relation to weight characteristics, a position has become evident which, without a great deal of exaggeration, can be defined by rephrasing a well-known expression: planning airplanes is first of all counting weight outlays. And indeed, the problem of weight is connected with the solution of all questions of planning, construction and finishing of an airplane in the process of testing. In other words, there are almost no problems which during creation of an airplane would be solved without considering its weight characteristics and the slightest negligence in this will lead to overweighting of construction. Among the problems which are also solved at all stages of the airplane's development, are reliability and economy, with the latter being more closely tied with its weight perfection. Light construction almost always provides an economic effect (true, the necessity for compromises is encountered), and solution of the basic problems of planning by means of optimization on the basis of the listed factors will lead to the creation of airplanes which are highly economic and capable of competing in their initial variation and provide for the development of modifications. The main questions in planning relate to the selection of the number of engines and the power-to-weight ratio, the dimensions of the airplane, and the principal layouts for controls and equipment and, /142 finally, the external and internal arrangement[4].

The number of engines and the power-to-weight ratio of the airplane have, as was shown in Chapter 7, an essential effect on its weight effectiveness. Therefore, when finding the best correlation between engine and airframe, one of the basic criteria is weight, and from comparative analyses of airplanes of the same type, it follows that a significant portion of the overall sum of weight differences often falls immediately on a deviation in the power-to-weight ratio. This is explained by the different airport conditions used during planning. These weight expenditures, however, are smaller with a lower specific engine weight, which is especially evident with an increase in the degree of by-pass (see Chapter 7).

[4] External arrangement means the relative placement of the parts of the airplane -- the wing, fuselage, empennage, gear and power units; internal arrangement indicates placement of the cabin, equipment components, fuel and useful load.

The effect of dimensions and parameters of various parts of the airplane on its weight effectiveness is no less significant. It is well-known, for instance, that with an increase in length (λ) and sweep (χ) of the wing, and with a decrease in its taper (η) and realtive thickness of its section ($\bar{c}$), the weight of its construction will increase. The use of a long wing is advantageous for cruising, takeoff and landing characteristics, however the resulting weight of the construction and the corresponding cost counter these advantages. An increase in χ improves cruise characteristics, increases construction height at the root portion and, besides this, increases the thickness of the wing with a corresponding decrease in its weight and an increase in the volume of the fuel tanks. However, these weight advantages are lost as the result of an increase in the calculated span of the wing ($\ell_s = \ell/\cos\chi$) with λ = const. However, it is no less important that an increase in χ deteriorates the lifting properties of the wing and necessitates an increase in complexity (and weight) of mechanization, which is necessary for fulfillment of the assigned takeoff and landing characteristics. The optimum values for λ and χ are determined in each actual case on the basis of weight or economic criteria. It is not advisable, for instance, to select a high degree of wing sweep for the purpose of attaining high speeds for airplanes to be used on routes on which these speed data are not used during operation Even when they are used, however, they will not in all cases lead to an increase in economy, and for achievement of high speed, it is necessary to make the construction heavier. For instance: the weight of a wing of a short-haul airplane weighing 40-45 t will increase by 350-400 kg with an increase in χ from 25° to 35°, and the weight of a fitted airplane with consideration for the rise gradient will increase by 800-900 kg. Also, regardless of a possible speed increase by 30-40 km/h, economy with retention of the takeoff weight and takeoff and landing characteristics is deteriorated and cost increases by 7-8%. /143

Another parameter, the relative thickness ($\bar{c}$), which essentially effects both the weight of the wing and flight speed, is also selected on the basis of a compromise between these factors. The selection of a wise law (nonlinear) of distribution of the relative thicknesses along the span of the wing allows attainment of high weight effectiveness with good aerodynamic data, since the thickness of the section at the wing root affects speed to a lesser degree and weight to a higher one.

Extensive mechanization of the wing makes the construction significantly heavier. Its weight in the total weight of the wing increased in an extreme case from 6-7% to 25-27%. Therefore, an analysis, as the result of which the amount of the effect and the weigth expenses are compared, serves as the basis for selecting the degree of mechanization and its corresponding parameters. Such extensive mechanization as three-part flaps with a changeable slot and slats along the entire span, used here first on the Tu-154, allows a significant increase in takeoff weight, and consequently in economy with the balanced field length to be maintained or

shortened while retaining the economy of the airplane. The takeoff weight in the second case is already increased as the result of an increase in construction weight and a corresponding increase in commercial payload from conditions of equal economy. The effect of complex mechanization is in any case significant and exceeds the weight expenditures. However, when selecting parameters for, for instance, a three-part flap, there is an optimum solution. Thus, an increase in c_y by means of increasing the angle of deflection and the length of travel to their defining values will lead to a noticeable effect. There is, however, a value for the length of travel beyond which a further increase in c_y will not compensate the additional weight expenditures, which increase sharply in this. It is understandable that in a similar analysis it is necessary to consider the gradient of rise ϕ_{r0}, whose value here is, true, limited by conditions of R = const and S = const. The increase in commercial payload weight is determined (under conditions of L_{rwy} = const) by the equation $\Delta G_{cp} = \Delta G_0 = \phi_{r0} \Delta G_{mech}$, where ΔG_{mech} is the increase in weight of mechanization due to the increase in complexity.

It should be noted that complex mechanization of the wing resulting in a significant increase in weight and complexity of construction has not received undisputed acclaim. Weighty technical arguments exist in favor of a wing with typical (moderate) mechanization, and large area. Preference might be given to either solution depending on the class of the airplane and requirements for its takeoff and landing characteristics.

The dimensions of the empennage have an effect not only on its weight, but also on the weight of the fuselage, whose tail portion is loaded with the weight of the empennage and the loads acting on /144 it. The area of the empennage is, as is known, in a definite relationship with the area of the wing and depends on its aerodynamic arrangement. Conditions of selecting its size and data on its dimensions are presented in Chapter 16, but it is appropriate to say here that providing normal stability and controllability in the airplane with minimum empennage area also promotes the creation of a light construction. At the same time, modern requirements for an ever wider center of gravity envelope lead to an increase in the relative dimensions and weight of the empennage and, consequently, also of the weight of the fuselage. Weight data on the empennage depend, of course, not only on its area. The selection of the length (λ) and taper (η) have not small significance. The shape of the empennage airfoil acquires a serious significance, especially when it is planned in the T-shaped layout. The optimum solution to this problem may noticeably decrease the specific weight of the empennage. The position of maximum thickness in the section of the horizontal stabilizer along the length of the chord, which affects the size of the construction height of the heavily loaded rear spar, has a significant effect on the weight of the construction. However, displacement of the maximum thickness toward the tail portion is connected with the angle of

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rudder conicity, and the latter is connected with the hinge moments. Consequently, on airplanes with a booster control system, the relative weight of the empennage may be decreased due to the possibility of displacing the maximum thickness of the section. It is also decreased in this case by removal of the balancing loads, if rudder conditions do not prevent this. The layout of the empennage, i.e. the relative placement of the horizontal and vertical surfaces, also have no small effect on weight effectiveness. The advantages of various layout remain disputed (they are analyzed below).

To determine the optimum (in a weight relationship) dimensions and configuration of the fuselage (primarily, the shape of the cross section and length), it is necessary to simultaneously examine the weight of the basic construction of the fuselage (longitudinal and cross-sectional members), the floor of the cabin and the weight of the empennage as a function of the total area of the fuselage. Only such a combined analysis will encompass the possible fuselage shapes (including the two-decked with large dimensions) and can lead to a proper solution. It is understandable that the assigned values for load capacity and passenger seating capacity and a striving toward maximum arrangement density in the parts of the loads and equipment lie at the basis of an analysis like this. This question is analyzed in detail in Chapter 7.

The selection of the principal layouts for various types of equipment also has a noticeable effect on weight effectiveness of airplanes. For instance, the alternating current system used on the Il-62 airplane allowed the weight of electrical equipment to be decreased by 17%. This is equivalent to a decrease in takeoff /145
weight by 1500-2100 kg[5] (with consideration for the coefficient of rise). A wise sound insulation layout and a tankless fuel system (used on the Il-18 partially and then on the Il-62 and Tu-154 fully) will also lead to economy in weight. Similar measures allow a significant reduction in the weight of the airplane.

Arrangement of the airplane as a whole, the passenger and cargo compartments and equipment components also has an effect on weight effectiveness. For instance, the new arrangement layout for seating installation (see Chapter 15) developed for the Il-62 airplane allowed a weight decrease for the fitted airplane by 4%, which comprises 12% of the maximum commercial payload weight, or 27% of the load transported at maximum range. Arrangement density in the passenger cabin increases the degree of fuselage space utilization and, with a set number of passengers, will lead to its minimum dimensions. Proper placement of equipment decreases the length of wiring harnesses, which promotes not only a decrease in weight, but also the power required (as a result of less loss), and consequently, a decrease in the weight of power sources. If

[5] Depending on flight range.

If we recall that the total weight of all harnesses on airplanes of the Tu-154 and Il-62 type significantly exceed 1000 kg, then the necessity for using a method of planning with the minimum weight and with equipment arrangement becomes clear. The Il-62 can serve as an example of a proper solution to this problem. The use of the new layout for takeoff and landing devices on this airplane, which was mentioned above, allowed many of the equipment components to be moved, not due to conditions of the airplane's center of gravity (which does not always lead to minimum weight), but due to conditions for minimum wiring harness length. The weight economy with this in the electrical equipment system alone comprised 330 kg.

Finally, the accuracy of weight and aerodynamic planning calculations, on the basis of which the engines and basic parameters of the airplane are selected, also have an effect on the weight of its construction. Besides this, the proper determination of the weight of the wing, fuselage and other parts of the airplane on the level of their minimum values, i.e. well-founded weight limits, also promotes the creation of a light construction. Exceeding the limits will lead to overweighting of the construction and equipment systems. The great meaning which is attached to accuracy in weight limits and their subsequent corrections is explained by the fact that they actually represent the basis for planning in the weight projection process itself.

10.2. Weight problems in construction. Construction weight is influenced on a level with planning factors and many design factors. The most significant of these are: determining the calculated loads, the selection of values for the coefficient of operational overloads, determination of strength margins, the selection of initial weight data and so forth (for more detail see Chapter 12). The theory for calculating airplanes for static strength is well developed, and as a rule, test results coincide with data from calculations. The main task here consists of simply determining the listed calculated values. /146

A significant part of construction is now planned on the basis of not only static but also fatigue strenth. All its form, connected with repeated loading or with actual fatigue are comparatively new, and the methods for their calculation are still not perfected. Therefore, it is expedient to create a construction with the minimum weight expenditures and conduct the necessary reinforcement after corresponding tests. The most important among calculations for fatigue is determination of stresses in elements of the wing which work under tension with consideration for the cyclic loads during takeoffs and landings, and also during vertical gusts of wind. It is also known that the amount of stress depends essentially on the character of flight, and on the quantity and placement of fuel. Its proper location and the selection of a wise sequence for its consumption will allow the achievement of a significant decrease in the amount of average stress in the wing and, consequently, a decrease in construction weight.

Searches for alternative ways to solve many problems, and the one examined in particular, can be very useful in the matter of creating light construction. Researchers of fatigue strength, for instance, assert that the most effective method for providing it is a reduction in the operational stresses by means of limiting the overall level of stress. This approach presupposes the necessity for considering stress concentrations. Another approach consists of searches to decrease stress concentrations by means of localized reinforcements from conditions of fatigue strength and leads to the creation of a light construction without limiting the overall level of stress.

An increase in weight necessitated by fatigue strength will lead to an increase in operating expenses as a result of an increase in the cost of the airplane. The reason for the latter, in addition to the increase in weight, is the complication of production technology and expansion of the volume of testing. However, these laws are compensated by increased safety and life. An immediate advantage is also a decrease in the required scope of servicing operations and monitoring on the condition of the construction in operation. These factors promote a decrease in operating expenses.

The selection of power diagrams of airplane construction and /147
kinematic diagrams of various installations has an essential effect on weight effectiveness. The use of monolithic constructions allows stress concentrations, which makes provision of fatigue strength more difficult to be avoided, and allows the creation of equal distribution of stresses without necessitating local reinforcement and allows weight to be decreased by no less than 9-10%. The wise location of construction elements, multipurpose utilization of their load-bearing parts and well-founded selection of configuration will lead to a decrease in weight. The solution of many technological problems will also affect construction weight. True, lightening often leads to an increase in manufacturing cost. The compromise is found on the basis of cost of the equivalent. The contradiction between weight and technology is more often exposed in problems of joints, junctions and connections, and this is not by chance, since the weight of the connecting elements of the airframe reaches 10% of the weight of its construction. Therefore, one of the most stable tendencies in the development of aviation is the striving toward reducing the number of connections to a minimum (in essence, a transfer to large-dimensioned panels and replacement of riveted construction with welded serves the same purpose). Where these are not successfully avoided, solutions with minimum weight expenditures are sought. For instance, the butt joints of fuselage sections in the L-1011 airbus "is accomplished with connections which work on shear instead of the connections usually used which work on tension. This leads to a weight savings on the order of 1360-1810 kg on each airplane, although the time required for connecting the two fuselage sections

is increased from 1 to 4-6 days."[6] The ever more widespread usage of welded connections in landing gear construction also leads to a significant effect. Only some of the multitudinous problems with construction are presented here, but they are all tightly connected with solution of the weight problem.[7] Therefore, a technically literate development of the drawing must always be accompanied by calculations for strength, weight and economy.

From the aforestated, it follows that weight effectiveness of the airplane is already compiled during the sketching process and even the pre-sketching planning, i.e. during the period when the dimensions and principle diagrams of the parts of the airplane and equipment systems are selected, and its further development is obtained during the period of technical and working project workup. While the appearance of the airplane is drawn in the first stage, the type of construction is selected in the second. Weight planning on the construction process on the basis of qualitative indices, i.e. on the basis of weight limits has not small meaning during the/148 latter period. An orderly and strict system of weight control during the process of developing drawings is the basis for planning with minimum weight. Furthermore, all stages of the weight control program must guarantee that the weight of the airplane will not move outside the limits of the planned values.

It is clear, naturally, that the minimum weight of a fitted airplane and, consequently, a high economy are achieved only as the result of optimum solution of all problems of planning and construction. However, the possibility for increasing weight perfection is limited to that part of the construction which does not exceed 65-70% of the weight of the empty airplane, and the remaining 30-35% consists of the weight of manufactured parts, which does not depend on aviation designers. "The load-bearing part of the construction, which comprises 50-60% of its weight, can be arbitrarily divided into parts. The first, providing static strength, without considering the coefficient of safety (= .15), comprises 55-60%. The introduction of this coefficient increases the share to 89%. The remaining 11% provide fatigue strength."[8]

In conclusion, it should be noted that on the modern level of planning, there are practically no unrevealed factors in which large and unused strength reserves can be included, which demands great inventiveness so that the next civilian airplanes will be noticeably lighter than the best of their predecessors. Therefore, a noticeable effect can be achieved only through careful study and summation of all small weight reserves. At the same time, it is doubtful that an airplane exists which would be impossible to lighten, which is explained by natural weight reserves.

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[6] Aviation Week, July 20, 1970.

[7] For problems connected with the use of new materials, see in Chapter 11.2 and 11.3.

[8] Aircraft Engineering, X, 1967.

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Chapter 11. On the "Weight Barrier"

11.1. General positions. For the modern stage of development, especially that of large-dimensioned airplanes, the methods used for creating light construction are already deficient. Searches for planning, construction or technological solutions cannot introduce essential changes, since their possibilities are not without limits.

It is known that the load ratio and productivity of passenger airplanes, along with perfection of construction, is increased by means of increasing the dimensions (tonnage) of the airplanes, which grows from generation to generation (see Fig. 1.3). This immediately reflects the peculiarity in the development of jet passenger airplanes, which consists of the prevalence of the increase in productivity over the increase in cost. Since an essential increase in speed and the coefficient of passenger loading is not occurring, an increase in productivity is achieved by means of increasing the dimensions of the airplane. Concerning the load ratio, the striving to increase it by means of simply increasing takeoff weight also has its limits, which also allow us to speak of the "weight barrier." At the end of the 1940's, analysis of the possibilities for high-tonnage airplanes (350-400 t) already led to the conclusion that the limiting and almost unachievable value for the load ratio of a piloted aircraft is a value of 0.7. They also came to a conclusion about the possible appearance of a "weight barrier" (before achievement of the 0.7 value). /149

The concept of the "weight barrier" is not yet agreed on, but its sense can be seen in the fact that an increase in weight effectiveness with a rise in takeoff weight will occur only up to definite limits. With its further increase, weight effectiveness either stabilizes or begins to drop. This limit is not absolute, and it moves toward high takeoff weights, but only with a change in airplane parameters or discovery of new means for creating light construction. The problem of takeoff weight is complicated by the rapid growth in airplane dimensions as the result of an increase in range and speed and a significant increase in the volume of equipment. The curve of takeoff weight as a function of range has a zone of bending, after which a small increase in flight range can be achieved only at the expense of a large increase in takeoff weight. The larger the dimensions of the airplane, the sharper this property appears. For the contemporary stage of aviation development, the concept of the "weight barrier" can be expanded and its sense can also be seen in the disparity between the required increase in effectiveness and the means for its achievement. A significant increase in effectiveness is necessary in connection with the increase in cost per 1 kg of weight of an empty airplane over the last 20 years by 600% (see Fig. 1.9), which is explained by the exclusive saturation of modern airplanes with expensive equipment systems and an increase in their construction and technological complexity [64].

The change in parameters and characteristics of an airplane and an engine, such as aerodynamic properties, specific loads on the wing, specific fuel consumption and specific engine weight and so forth, will lead to a displacement of the "weight barrier" towards larger takeoff weight values. A growth in airplane construction effectiveness will also promote this movement. Thus, as a result of an increase in flight speed which was connected with the use of a thinner wing section), the increase in specific loads (from the calculated weight) and complexity of means for increasing the lift force raised the level of stresses in the construction of the wing. A graph (Fig. 3.10), illustrating the tendency of this increase as a function of time[9], supports the position on increase construction/150 effectiveness.

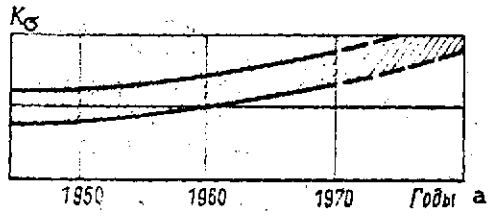

Fig. 3.10. Change in the coefficient of stress (limiting values) according to data from work [90].

Key: a. Years

In cases where productivity of the airplane is maintained, an increase in the listed parameters and characteristics will lead to a decrease in takeoff weight. The amount of this decrease is greater as the airplanee's available range increases. Many analyses, one of which does not pretend to high accuracy, lead to similar results, graphically illustrating this position (Table 3.1). The results of such analyses[10] support the conclusion that improvement of the weight characteristic is now no easy matter, especially for airplanes flying short routes. By the way, it is /151 curious to note that the results of a similar analysis for supersonic airplanes is more reassuring (Table 3.1).

The idea of creating supersonic passenger airplanes (SST) with a flight range of over 4500-5000 km finds support due to optimistic forecasts for relatively essential improvement in their characteristics. This suggests belief in the fact that they will finally prove to be more effective subsonic airplane with an equal flight range. The effectiveness of SSTs and, first of all, their productivity will increase primarily by means of an increase in speed and flight range. At the same time, a further increase in productivity of subsonic airplanes will be achieved by means of increasing the commercial load ratio. This is connected with the problem of increasing takeoff weight, and in the final analysis, with the problem of decreasing the relative weights of airframe construction, power unit and equipment. Concerning flight speed, although its value continues to increase, the value for the M number

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[9] Astronautics and Aeronautics, II, 1967.

[10] ICAS, Paper No. 66-1.

will not exceed 1. The advisability of a transfer into the area of the value of M = 1.2-1.4 is disputed, especially for airplanes having a short flight range.

TABLE 3.1. DECREASE IN AIRPLANE WEIGHT WITH THE IMPROVEMENT OF VARIOUS PARAMETERS AND CHARACTERISTICS (%)

Designation		Subsonic airplanes			Supersonic
Calculated flight range in km		450	2000	5500	5500
Payload (% of takeoff weight)		22	19	13	7.5
Decrease by 10%	of frontal resistance	1.4	3.8	10.5	21.0
	of specific fuel consumption	2.7	5.4	10.5	20.0
	of specific construction weight	6.5	6.9	7.0	9.4
	of power unit weight	2.3	2.0	2.0	4.1

A decrease in the relative weight of the power unit is possible with a further increase in the degree of by-pass.[11] Weight of equipment will apparently increase due to complication of systems and automization of pilotage and will increase with the development of principally new equipment elements. The relative weight of the construction will increase with an increase in takeoff weight [62] and [91] with specific wing loading (p) unchanged and will decrease if wing loading is increased. However, the value for p does not exceed 650 kg/m^2 at the present time. A further essential increase is apparently limited (by the possibilities of modern aerodynamics and wing mechanization) to limits of 725-750 kg/m^2. At the same time, progress in the area of decreasing the relative weight of construction is fully possible, but it will be achieved by other means.

11.2. On new materials. For solution of the weight problem, cardinal means, one of which is the widespread usage of new materials with higher relative strength, are now necessary. True, the possibilities for more widespread usage of the aluminum alloys used now have apparently not been exhausted. A further improvement will apparently occur along the lines of increasing static and fatigue strength, or decreasing specific weight.

[11] The m = 5-8 achieved are not considered limits.

Titanium has the most promise for widespread usage in the construction of subsonic and supersonic airplanes. Over the last two decades, it has ceased being a comparatively rare material and has become a material whose production is counted in the tens of thousands of tons per year. /152 However, alloys of titanium are in the earlier stages of development than those of aluminum, and can therefore be examined only as having great potential possibilities.

It is well-known that in the construction of civilian airplanes, titanium alloys, regardless of their widespread possibilities, were in the past used to a significantly smaller degree than in the construction of military planes. In spite of this, in some civilian transport airplanes, the weight of elements made of titanium alloys now comprises nearly 3% of the weight of the construction. Experience in usage and further research showed that the weight savings in cases of its use reached 20-25%. With this, these alloys can compete not only with steel at high temperatures (for supersonic airplanes), but also with aluminum at low ones. Titanium alloys allow a noticeable decrease in the weight of design elements working basically on tension or elements subjected to severe compression. Titanium welds beautifully, which introduces an additional gain in weight, and therefore it is used in the construction of landing gear, in the manufacture of pipelines for various systems and so forth. The use of titanium monolithic panels in the construction of subsonic airplanes must also lead to a decrease in weight. It is supposed that each panel must be 5-10% lighter than an aluminum one (depending on the degree of loading). Titanium alloys have long been used in the construction of engines, noticeably decreasing their specific weight. The use of titanium fasteners of the same dimensions for replacing steel bolts and with a smaller diameter when replacing aluminum ones has proved to be especially effective. (The latter allowed the distance from parts' edges to be reduced, which led to an additional weight savings.) With this, it successfully competes with steel and aluminum in a wide range of stresses. Airplane fasteners have great significance, in that their cost reaches a significant figure. Thus, on the Boeing 747 airplane, it comprises 5% of the cost of the airplane.[12] The widespread usage of titanium alloys is at the present time prevented by the low coefficient of utilization. Thus, according to data from the Boeing firm,[13] 4-4.5 kg of this alloy are expended for each kilogram of titanium construction, while the coefficient of utilization for aluminum comprises 0.5. It is proposed that by 1975, the coefficient of utilization for titanium may be increased up to 0.33. Titanium construction costs significantly more as the result of the high cost of the material, and also becasue of the complexity of its machining. It must, however, be evaluated with consideration for the change in weight and flying characteristics of the airplane. Then the economic effect will not only compensate the expenses, but

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[12] American Aviation, February 17, 1969.

[13] American Aviation, July 13, 1969.

profitability will increase, and the growing usage of this material must lead to a further decrease in its cost. /153

New high-strength steels have also begun to be used. For instance, the gear of the C-5A airplane are manufactured of heat-treated steel with a specific strength against stretching of 195-200 kg/mm^2, is 3% lighter than the gear manufactured of steel with a σ_b = 183-195 kg/mm^2.

In the past, beryllium was used in airplane construction, but only for the manufacture of a highly limited number of components, for instance, for wheel brake disks for a military transport airplane. A significant effect was achieved with this, which was provided by the exclusively high heat capacity and heat conducting properties of this material, which allowed disk temperature to be reduced during intensive and extended braking. However, beryllium disks are considered unacceptable for passenger airplanes in view of the danger of formation of cracks under the effect of shock loads. The turning rudder on the American Douglas "Phantom" airplane is manufactured of beryllium. The weight savings achieved comprised 30% (by comparison with rudders manufactured of aluminum alloy). Due to its low density (γ = 1.8), beryllium is a promising material (but its deficiencies (brittleness, toxicity and high cost) may somewhat limits its use. It is thought that in constructions which are critical in rigidity, a weight saving of 15% might be achieved through the use of beryllium (by comparison with aluminum), and in those critical according to strength and fatigue longevitiy, the gain might comprise 5%. However, attempts at developing an alloy of beryllium for widespread usage in airplane construction has not yet been crowned with success.

The development of new aviation materials which correspond to the increasingly complex planning requirements and operating conditions, i.e. materials capable of extended and reliable work and possessing the assortment of required properties and, first of all, high static and fatigue strength has exclusive significance. It is these very properties which determine weight and economic effectiveness. The value in the development of the new materials is determined not only by the acuity of the weight problem, but also by the striving to achieve a 20 year calculated operating period for airplanes with economic servicing.

It was established comparatively long ago that the strength of solid materials can be increased if a thin wire or fiber is manufactured out of these materials. This occurs as a result of a decreased probability of the appearance of surface damage or defects, which are sources of failure. This feature and the possibilities which appeared for composition materials led to widespread investigations, development and then improvement of materials on the basis of high-module graphite fiber and boron fiber. Now, the technically and economically expedient creation of composition materials /154 with sapphire or tungsten rhenium fiber and on the basis of a nickel or titanium alloy is being investigated. At the same time,

materials reinforced with beryllium fiber are considered to be distinguished by their better plasticity and lower weight by comparison with similar materials reinforced with fibers of other types. There is also no doubt as to the possibilities for further improvement of the characteristics of fiber glass, relatively widely used, with respect to both specific rigidity and specific strength.

The first tests, beginning in 1967, of the use of synthetic composition (combination) material can encouraging results and allowed optimistic forecasts to be made about its widespread usage in the future. They will lead to a decrease in construction weight and will allow the manufacture of airplane parts on automatic machines, and they will also lead in the future to a decrease in the cost of the material itself. It is understandable that in the beginning its cost was great and the advisability for using new material appears when the weight savings justifies the expense, of course with consideration for the concept of aviation weight. On the basis of preliminary calculations, specialists reached the conclusion that "an airplane construction transferred to composition materials from the drawing table will weight 30-50% less than construction out of normal materials."[14] Others assert that "composition materials with boron fiber may provide a weight saving on the order of 18-24%, and the maximum usage of this material would yield a weight savings of no less than 40%. Graphite materials uncover still greater possibilities!"[15] These statements are apparently somewhat optimistic, but if the weight savings comprises 25-30% of the weight of the construction itself, this will lead to a new qualitative leap. In the construction of a modern typical airplane, the proportion of nonmetal materials is very small. It does not exceed 9%, with 75-80% of the weight belonging to aluminum alloys and 16% to steel.

The first composition materials used were resins reinforced with fiber glass. Out of these materials are manufactured (for instance, on the Boeing 737 airplane) parts of the flaps, farings, vertical stabilizer, rudder surfaces, some panels and auxiliary elements. The high strength and rigidity with the low weight of these plastic materials depends on the content and placement of the fiber in the resin matrices. More widespread usage of them began with the Lockheed C-5A and Boeing 747 airplanes. On the latter, panels of fiber glass and light alloys comprised half the area of the wings and empennage. In the future, materials have begun to be /155
developed in which the metal matrix (of aluminum or magnesium alloys) is reinforced with high-strength fiber (for instance, of boron). A panel of this material, differing from reinforced plastic, can absorb loads in all directions. These materials are more promising in relationship to weight and economy than materials with a plastic matrix. Composition materials bonded with fibers

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[14] Airoplane, December 27, 1967.

[15] Tech aer, October 1968.

of boron, graphite or silicon carbide are distinguished by high static and fatigue strength at both high and low temperatures, and low weight. For instance, a construction material on the basis of high module graphite fiber (created by the Northrop firm) is 40% lighter than aluminum and 4.5 times as light as steel. Another material (developed in England), containing 50% carbon fiber (by volume), has a destruction stress against rupture of 105 kg/mm^2 with a module of flexibility of $1.76 \cdot 10^6$ kg/cm^2. The destructive stress for rupture of this material is almost double that for an aluminum alloy. In rigidity, it exceeds aluminum alloy by 150%. In specific weight, it is twice as light as aluminum alloy and five times as light as steel. The deficiencies in this material include high cost, low shear strength between layers and brittleness.

The widespread usage of composition materials in airplane construction will in the future lead to a decrease in cost, and due to a significant decrease in construction weight, the creation of even more gigantic and productive passenger and transport airplanes will become possible. The capability of a new material to maintain strength characteristics at high temperatures allowed its use in the construction of engines, in particular for the manufacture of compressor blades in large turbofan jet engines. It should be noted that the new materials also require a new approach to the planning of aviation constructions with consideration for their peculiarities. For instance, in construction of composition materials, orientation of the reinforcing fiber has an essential value.

The proper selection of materials has a first-degree value for any airplane, since it immediately affects not only the weight, flying and economic characteristics, but also the operational reliability of the airplane, a factor which is usually considered in analysis of the effectiveness of new materials. Generally speaking, the way to increase weight effectiveness of construction with the use of lighter and stronger alloys is not new. The mechanical characteristics of construction materials used in airplane construction have systematically increased the past use of, for instance, B-95 alloy or the use of titanium (even in limited quantity) led to a definite weight decrease. The new factor in the modern formulation of this problem is its qualitative solution, which must also lead to progress, and the widespread usage of composition materials must even lead to a revolution in airplane construction. /156

11.3. An example of overcoming the "weight barrier" might be the plan for the Lockheed C-5A transport airplane, on which the amount of data published was somewhat greater than that for the Boeing 747 airplane. It should first be noted that this class of airplane has several interesting peculiarities with respect to weight. The load ratio of these airplanes, according to landable load (by comparison with the commercial load ratio of passenger airplanes of equal tonnage) is somewhat higher, but the relative weight of the airframe is also somewhat higher. Both of these lead to an increase in the calculated values for takeoff and landing

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weight, since the weight of the airplane without fuel is increased, which in its turn makes construction of the airframe heavier. True, a tendency has also been observed toward decreasing the gap between takeoff and landing weights in passenger airplanes for the sake of eliminating refueling at intermediate airports and shortening standing time. In this case, some increase in the weight of the empty fitted airplane is economically justified. Another peculiarity of these airplanes is, as was noted, the weight classification, which reflects their purpose, differing in this from that established for passenger airplanes.

A graph (see Fig. 3.11, a), from which is it evident that the load ratio of the C-141A and C5-A [83] transport airplanes weighing 143 and 346 t proved to be equal (points 1 and 2) can serve as an illustration of the aforestated about the "weight barrier." If new ways to reduce weight had not been found in the second of these /157 airplanes (with which the text deals later), however, its load ratio would have turned out to be even lower than in the first (point 2 a). It was retained (regardless of the high relative weight of the airframe) due to a noticeable decrease in the weight of the power unit, which is connected with the use of engines having a high degree of by-pass. Change in the inclination of curves "a" (see Fig. 3.11, a) does not yet allow us to speak of the "weight barrier," although its effect is talked about here. The curve of the relative weight of the airframe (see Fig. 3.11, b), which changes its curvature provides more of a basis.

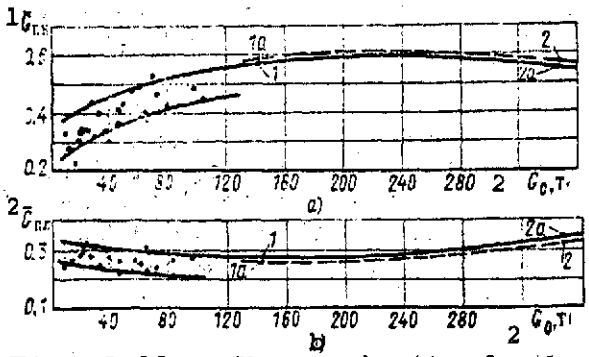

Fig. 3.11. Change in the load ratio (a) and the weight of the airframe construction (b) of transport airplanes with an increase in takeoff weight.

Key: 1. $\bar{G}_{tl}$; 2. $\bar{G}_{af}$

A decrease in the total load ratio can be explained by various reasons, part of which are connected with fuel, for instance, with the significantly lower fuel consumption by the engines mentioned, and by withdrawal from the determined correlation between the increase in the airplane's tonnage and fuel reserve which existed up to recent times (see Fig. 3.2).

The comparison of the relative weight of the airframe construction and the value for $\bar{G}_{ef}$, expressed by Eq. (3.6) which has been agreed on to be called the effective load ratio of the airframe construction represents interest in this plan. Comparison of their values for airplanes with very different weights will lead to interesting conclusions. Thus, the values of this amount for airplanes with coordinates of points 1 and 2 (see Fig. 3.11, b)

are equal to 0.8 and 0.93 respectively. Thus, the effective return of the second will improve, even at the same time as the relative weight of the airframe construction (see Fig. 3.11, b) increases. The theoretical relationship G_{cp}/G_{ac} must increase, but up to what limit is still not clear.

The incongruity mentioned can be explained, in particular, by the redistribution of the relative weight values for parts of the airplane. Consequently, the question of stability of values for airplane part weights, which was observed at separate stages of aviation development (and was rather extended at first), has an immediate effect on this. It even allowed expression of a proposition about its absolute character and use of the relative weight values as criteria of construction perfection. Based on this, it was assumed, for instance, that an essential deviation of the partial index value from normal toward the high side testified to an unsuccessful or obsolete construction, in which the material was unwisely used. A deviation toward the low side allowed the supposition that the airplane or its parts satisfies the requirements outlines for it to the best degree or that innovations are used which in some measure foresee further development. A similar proposition was first of all related to the airframe construction, whose relative weight in airplanes in the 1930's and 40's comprised 28-32%. However, in passenger airplanes of the 1960's, it was reduced to 22-24%. At a certain stage, an assertion on the /158
stability was justified, however a systematic redistribution of relative weights in the overall weight balance of the airplane is occurring with the development of aviation. It is clear, for instance, that with a transfer from the turboprop power unit to the jet one, and then to engines with a high degree of by-pass, the relative weight of the engine group dropped. At the same time, it constantly increased in all equipment systems. All this in turn had an effect on the value for the relative weight of the airframe.

Regardless of the complexity of the weight problem in planning large-dimensioned passenger airplanes, a sharp increase in tonnage will attain a significant technical and economic effect.[16] This is evident from the following example. On one airplane weighing 350-400 t in comparison with two weighing 175-200 t, there is not only less weight, but equipment cost is also significantly lower. Besides this, consumption, and consequently cost of fuel per unit of flight productivity is also lower. Concerning the total cost of engines for these two variations, it is approximately identical, since the cost of a unit of thrust in large engines increases insignificantly (see Fig. 1.16). It should, by the way, also be

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[16] In evaluating the effectiveness of military transport airplanes with consideration of possible losses during performance of operations and other peculiarities of these airplanes, this assertion may also be correct.

noted that the realtive value for the cost of engines and equipment comprises over half of the total cost of the airplane.

Turning to the major question in this section, it should first of all be stated that overweighting of construction in the first period of development of the drawings, or more precisely, deviation from the weight program, which upset the Lockheed firm during creation of the C-5A, cannot be considered exceptional. The amount of these deviations and the tendency toward growth (instead of a decrease) of the relative weight of the airframe construction (change in the curve on Fig. 3.11, b), i.e. the appearance of the weight barrier was apparently unexpected. Measures which allowed initial weight to be significantly decreased and a definite effectiveness in construction to be achieved therefore represent doubtless interest. They are interesting in that they predetermine the way for overcoming the weight barrier. These first of all include:

1. Intensive use of titanium in the construction of the wing (spar boom cap flanges, flap rails and carriages, slat guides, fittings and so forth), the fuselage (main frames), and the gear (forgings for legs), which decrease the weight of the airplane by 1134 kg. The use of titanium fastenings instead of steel ones led to an even greater effect (3356 kg), since the number of fastening parts on similar airplanes is counted in millions of units.[17] The /159 total weight of the parts made of titanium, not counting fastenings, comprises 3855 kg.

2. The use of beryllium alloy for the manufacture of brake disks (816 kg).

3. The widespread usage of forgings, monolithic construction and chemical milling.

4. The use of welded connections in gear construction.

5. The use of stricter tolerances for all machining of parts and other technical improvements (907 kg). Besides this, nearly 2300 m^2 of composition materials were used in the construction of the C-5A, while a total of 552 m^2 was used in construction of the C-141A. This is honeycomb panels and plastics reinforced with fiber glass, which are used for the manufacture of the front edges of the wings, slats, rudder and panels for the fuselage and fairings. It is said that floor beams manufactured of these materials prove to be 35-40% lighter. In the future they will apparently be used for the creation of load-bearing panels, spars and other load-bearing elements.

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[17] In the Boeing 747, 2.5 million units costing 1 million dollars. In the Lockheed L-1011, 4530 kg and 11,340 kg of high strength steels (Aviation Week, July 20, 1970).

Special attention was paid to the weight characteristics of equipment, the miniaturization of instruments and reduction in the weight of wires, in particular by using flat cable. In the C-5A, 132 km of wires weighing 1350 kg were laid, and in the C-141A, 68 km weighing 1130 kg were used. The savings reached 40%.[18] Fulfillment of the weight program in the equipment system provided a decrease in its weight by 25% by comparison with the C-141A. In relation to equipment, a bonus system was also used, for which the Lockheed firm paid its subcontractors to decrease weight in series blocks of electronic equipment a sum ten times greater than the amount of the fine (150 dollars), which he had to pay his customer for every pound of overweight on the C-5A airplane. It is well-known that lightening of parts is often connected with an increase in their cost and that there exists a definite economic evaluation of means with which a reduction in construction weight is achieved. Thus, during planning of the C-5A, a weight saving of 1 kg was considered justified if expenditures did not exceed 444.5 dollars per airplane.

The most singificant of the measures listed is considered the widespread usage of titanium, especially in fastening elements. The higher specific strength of titanium by comparison with steel led to lightening of the airplane construction by approximately 1%. The fastening system with intereference and other features[19] led to an additional decrease in weight whose total amount reached 4% of the total design weight. Such a significant results was achieved both on the qualitative side of the problem and on the quantatitive one, which is illustrated in Table 3.2.[20] /160

The total weight of the lightening listed above (6213 kg) comprises nearly 6% of the weight of the airframe construction; 4.2% of the weight of the empty airplane and 5.2% of the maximum weight of the load. In order to imagine how significant this amount is, we recall that the part of the load bringing in profit from a passenger airplane flight (with $K_{pl} = 0.65$), usually does not exceed 25-30%. All these measures, highly noteworthy in their character and used on a wide scale, still did not solve the problem as a whole; although they led to significant results.

The measures taken on the C-5A allow the assertion to be made that if they were realized in time on the C-141A airplane, its construction would have been "more than 5% lighter" [83], and consequently it could have comprised no more than 25.5% of the takeoff

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[18] A recalculation was apparently done with consideration for required energy.

[19] While investigating the effectiveness of various types of fastening, it was considered that a tight fit, improving the fatigue characteristics of hole fastenings, could also be attained with the use of steel fittings.

[20] SAE Journal, IV, 1969.

weight (as opposed to 27.0% -- see point 1 a on Fig. 3.11, b). Points 1 and 2 on these curves relate, as was indicated, to the C-141A and the C-5A respectively [83]. Points 1a and 2a relate to the same airplanes but the recalculations were found on the basis of data presented above: 1a corresponds to conditional introduction on the first of these of all lightening measures which were conducted on the second and point 2a on the contrary relates to the elimination of these measures on the C-5A airplane. In this way, the curves combine data of airplanes conditionally brought to the same technical level. Changes in the curves on the sections 1-2a and 1a-2 indicate that partial measures, and even significant ones, are still insufficient to retain the slant of the curves or even keep them on a level of $\overline{G}_{ac}$ = const; $\overline{G}_{tl}$ = const. /161

TABLE 3.2. WEIGHT EFFECT OF USING TITANIUM FASTENINGS

Reason for weight reduction	Savings in fastener weight %	Savings in design weight %
Work of titanium fastenings (instead of steel) on static strength	22	0.85
Decrease in distances to edges with the use of titanium fastenings instead of aluminum ones	3	0.12
Increase in fatigue strength (decrease in thickness)	75	2.93
Total:	100	3.9

The effective ways for decreasing the weight of the construction plan were examined above. Searches are also being conducted, naturally, for design solutions, part of which will lead to an immediate decrease in the weight of the fitted airplane, the other part leading to the decrease in the weight of fuel and an increase in payload (with G_0 = const). In the second case, the weight of the fitted airplane is either maintained or even increases, which is typical for cases in which the aerodynamic shape of airplane parts is improved. For instance, for the same C-5A, models were manufactured of five variations of farings for parts of the wings and fuselage (with various dimensions and angles of inclination). During a quantitative evaluation of weight and resistance, a modified faring was used which was 500 kg heavier than the initial one but had a lower resistance, allowing payload weight to be increased by 6800 kg.

The weight problem during the planning of the Boeing 747 was solved in the same way by means of widespread introduction of titanium (its total weight comprised nearly 4000 kg), the use of

stronger aluminum alloys, honeycomb panels made of fiber glass,[21] the use of steel tubes in the hydraulic system, the widespread usage of aluminum electrical conductors, a decrease in the number of connections through the use of longer panels (up to 32 m) and monolithic parts and so forth. A program for reduction of "the initially increased" weight led to lightening of the construction by 9 t, with which the effect was achieved primarily through the use of new materials. The dependencies represented on the graphs (see Fig. 3.11, a and b) and the materials used allowing illustration of the acuteness of the weight problem and the appearance of the "weight barrier" are based, as was noted, on statistics on transport, and not passenger airplanes, although both have a common character and they also relate to passenger airplanes to an equal degree (see Fig. 3.1).

In conclusion it should be stated that the "weight barrier" can be overcome in the modern stage through the use of new construction materials, a striving for more accurate determination of the actual loads by means of optimization of all planning and construction solutions, improvement of technological processes and so forth, i.e. by means of increasing the effectiveness of construction and the machine as a whole.

Chapter 12. Formulation of Weight Characteristics and Dynamics of Their Increase in the Planning Process /162

12.1. Formulation of the problem. The actual weight of the first experimental empty airplane as a rule exceeds the theoretical weight found as the result of the weight calculation. In these cases, the questions always arise: is the calculation accurate or is the construction overweight? Is it possible to obtain agreement between actual and planned data? The task of the chapter is an attempt to answer these questions[22] and show that changes in weight data during the creation period of an airplane are an objective conformity, but agreement between the actual weight and the planned weight at the same time is possible (of course within limits of the definite tolerance).

The theory of weight calculation is younger and, naturally, less developed than the theories of other planning calculations. Therefore, determining weight characteristics with the same accuracy as, for instance, aerodynamic or strength characteristics is rather complex. The fact of the matter is that the best of the formulas for determining the weight of airplane parts has an admissible error

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[21] Curious that panels of fiber glass and light alloys also occupy half the area of the wing and tail empennage on this airplane.

[22] The creation of an airplane is understood to mean the development of the sketch plan, working drawings, construction, testing and finishing.

of 3-4%, and 2% must be considered an indicator of acceptable convergence of weight, like other characteristics. Incidentally, weight formulas were in the past derived only for separate parts of an airplane, and only recently have systems for the weight equations necessary to solve the total problem of optimum planning begun to be developed. Still, the accuracy of weight, like strength calculations depends primarily on the initial data, and the latter are connected with an extensive workup of the plan. Besides this, the weight calculation has a number of peculiarities. These include, for instance, the actuality of weight problems. Common solutions are significantly fewer here. Aerodynamic and strength characteristics are connected with a limited number of factors, whose character in the planning process is distinguished by its constance. The first of these include: the power-to-weight ratio, wing area and configuration of the airplane. Concerning strength of the airplane, it is connected with the acting loads and power layouts. Weight calculations encompass everything that relates to the other two, and additionally, arrangement peculiarities, all equipment systems, materials used, technology, or in a word, the entire airplane as a whole. Descriptively expressed, the weight calculation is a mirror of the entire airplane and all changes which occur during the process of its development (the actual weight of the airplane is a combination expression of almost all its properties). Consequently, partial changes in the project, refinement of the calculated data and other changes occurring during the process of workup of the drawings are reflected on the weight data and will lead to the necessity for correction of the weight calculation and refinement of the weight characteristics.

It is known that the proper determination of weight characteristics of an airplane during the very first stages of planning has exclusive significance, but at the same time it is an extremely complex matter. A confirmation of this could be some interesting facts from the development of the American Boeing 2707 SST, about which one of the firm's managers said: "During the preliminary planning stage, the most competent specialists using the most modern equipment determined the weight of the construction, which was checked by other competent specialists who announced that the weight was correctly calculated. However, when the detailed planning began, it became clear that the weight of the construction exceeded that of the calculations to such a degree that the entire payload (comprising 8% of the takeoff weight) was actually lost" [93]. /163

The matter is not quite as acute on subsonic airplanes, although there also the effectiveness is sharply deteriorated with an increase in construction weight as opposed to planned weight. The amount of miscalculation in determining the weight depends on the degree of innovation, which is also relatively high in, for instance, airbuses.

Overweighting construction will always lead to unfulfillment of some of the planned characteristics for the airplane, either

load capacity as a function of range or takeoff and landing characteristics. To maintain flight range (which is necessary for passenger airplanes which are planned for actual routes) it would be necessary to decrease the weight of the commercial payload by an amount equal to construction overweight. If reserves in strength and thrust allow an increase in takeoff weight to maintain this load, than the planned takeoff and landing characteristics would not be fulfilled. Shipping costs increase in both cases, in the first to a larger degree and in the second to a lesser one. If overweighting is observed during the period when it is not yet too late to introduce partial changes into the project, the flight characteristics and shipment costs can be maintained by means of increasing the commercial payload, engine thrust and wing area.

Analysis of weight characteristics in modern airplanes allows the assertion to be made that unjustified overweighting of constructions rarely occurs. True, establishment of the presence of overweighting is possible on the basis of a rather complex analysis of weight and strength of the construction or by means of parametric analysis of a number of airplanes of the same size. In the second case, weight evaluation of the layout peculiarities of the airplanes and an evalution of the differences in geometric and flight data are required. As the result of such analyses, the reasons for a justified divergence of the weight data compared during a comparative evaluation of the airplanes are, as a rule, successfully explained, i.e. the minimum value for weight expenditures required for the achievement of various properties or features of the airplane is explained. During the creation of an airplane, it is advisable to conduct similar or other analyses during the process /164 of sketch planning and development of the working drawings, where it is still possible to lighten construction painlessly. The economic effect of lightening, even with significant losses in time, is difficult to overestimate.

It should be noted that some increase in weight as opposed to that provided by the program is characteristic for the initial period of a working plan. Vigorous measures are taken after that, and by the time 50-60% of the set of drawings is prepared, the situation is successfully corrected. Another weight increase is observed during the completion stage, but it is insignificant. The degree of its increase depends on the rate of the project's development, and short planning periods will lead to an overweighting of the airplane. Many firms, for instance, Boeing[23] when planning the 747 passenger airplane and Lockheed,[24] when developing the C-5A military transport airplane came to the same conclusions. The last information relates to the areas of weight planning and weight control. Their meaning will help to take the necessary measures in good time.

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[23] Flight, December 19, 1968.

[24] SAWE, Technical Paper, No. 653, 1968.

12.2. On the increase in the weight of the fitted airplane during the process of its creation. Overweighting of an airplane is often judged on the basis of a divergence between actual and projected weight data. However, it is difficult to agree with this approach to weight evaluation of an airplane. The construction of an airplane can also be overweighted in a case where these data agree, and it may prove to be ideal with their significant divergence. Overweighting an airplane, regardless of coincidence of actual weight characteristics with planned ones, is possible as the result of various reasons. One of these is re-sizing of the airplane, or selection of unwise geometric parameters. Then the airplane may be overweighted as if in the embryo itself. Consequently, the commonly accepted idea of overweighting of an airplane must now be expanded and defined as the presence of weight not justified not only by technical requirements but also be economic expediency. The technical ones includes, first of all, strength, and then airport requirements, takeoff and landing characteristics and others. Economically unjustified weight expenditures can include, for instance, a greater degree of wing sweep for the achievement of speed, the use of which will not lead to an economic effect for the given airplane.

An increase in the weight of an airplane and its construction in the process of development are inherent in the normal process of planning, i.e. it is a regular inevitability. This occurs as the result of:

1) The gradual entry and refining of calculations, layout and /165 other initial data for weight calculations of subsequent approximations;

2) The unavoidable divergence from the initial project, which is connected with its gradual development, and sometimes for the sake of fulfilling the guaranteed characteristics or as a result of partial changes in the requirements of the orderer, or the appearance of new equipment and so forth;

3) Technological requirements for series production;

4) Detail work after static and fatigue tests;

5) Finish work after flight tests;

6) Deviation in the weight of finished products, whose weight reaches 30-35% of the weight of the fitted airplane.

For founding the basis of this increase, the author and foreign researchers [77] conducted analysis of a rather large amount of statistical material, whose results allowed notation of a definite conformity in the increase of all weight characteristics of an airplane during the process of its planning and operation. The explanation for such a conformity has a practical value, since for

weight planning in the process of projection and the subsequent development of the airplane, an accurate forecast of the possible changes making up the weight of the airplane at all stages in its development and operation is necessary. The conclusion of a coefficient which considers the degree of change in weight characteristics during the period from the sketch plan to weighing of the first experimental and first series airplanes has a great meaning in connection with this.

The analyses mentioned complement each other. While data on modern passenger airplanes with turbojet and partially with turboprop engines is used in one of them, the other is based primarily on materials concerning airplanes with piston and turboprop engines. Of the 28 airplanes and their modifications examined during the second analysis, only the data of four airplanes was encountered in the first, in which materials concerning 19 airplanes and their modifications were used. Fig. 3.12 shows the average values for the increase in takeoff weight (ΔG_0) and weight of the fitte airplane (ΔG_{ef}) at the stages of project development, testing and finish of the experimental model, and also workup of the series drawings and, finally, during the process of series production and operation. Study of the given problem allowed a graph to be constructed (Fig. 3.12, 3.13) and some conclusions to be drawn.

1. The amount of the coefficient of increase in fitted airplane weight depends on a degree of innovation and other factors. If, for instance, the engines and equipment are selected from existing ones, the increase will be less, and if they are being planned at the same time, it will be greater. It also depends on the experience of the planning organizations.

2. In development of modifications, the value of the coefficient is lower. /166

3. The character of the reasons for the increase in weight shows that the examined coefficient does not relate to cases in which there is a partial review of the project connected with an increase in productivity (i.e. range or load capacity) of the airplane. The latter is also inherent in the process of creation for passenger airplanes, but must be considered with another coefficient whose value lies within the wide limits of 1.08-0.2. While an increase in the theoretical values for fitted airplane weight and a corresponding increase in takeoff weight during the planning process is practically unavoidable also with retention of productivity, an increase in these weight data with a rise in productivity is even effective, since expenditures in mass of the airplane and fuel energy per unit of productivity decrease sharply with this.

4. The character of the weight change curves in the process of operation (see Fig. 3.12) can be explained firstly by perfection of the airframe and equipment and secondly by the more intensive

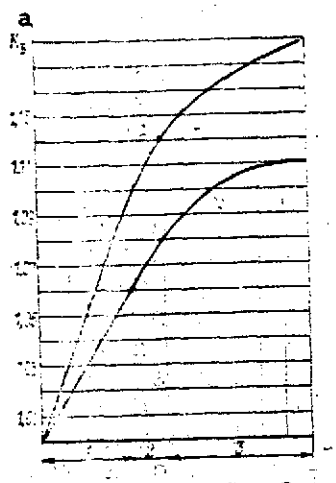

Fig. 3.12. Coefficient of increase in takeoff weight (a) and empty airplane weight (b) (average values) in the process of creation and operation
1 - from project to experimental; 2. from experimental to first seris; 3. during the process of operation

Key: a. K_i

development of the airplane during the first years. The latter occurs through construction reserves and the appearance of new modifications. In the later period, the intensity of development slackens as a function of structure reserve exhaustion and also of the appearance of airplanes of subsequent generations.

The results of treatment of the statistics allows the amount of the coefficient of fitted airplane weight increase during the process of its creation to be determined, and it lies within limits of K_i = 0.06-0.08. Judging from data published by the Lockheed firm [79] the value of K_i = 1.06 is also justified for military transport airplanes. This value, as the analyses mentioned above, is unavoidable and stable. /167

5. An especially clear division of the two principally different reasons for changes in weight characteristics of an airplane during the planning process is necessary. The first of these is connected only with the specifics of weight planning examined above. The second is connected with an increase in takeoff weight for the sake of increasing passenger seating capacity, or increasing the initial assigned (or accepted) flight and takeoff/landing or operational characteristics, and also with improved equipment being fitted onto the airplane. The measure of the increase in the fitted airplane weight in each of these cases is naturally different.

12.3. On the rise in airplane takeoff weight. The discourse above concerned the change in fitted airplane weight, but the change in takeoff weight also occurs for various reasons. While during planning, for instance, it becomes clear that the weight of the fitted airplane cannot be held at the level on which the initial takeoff weight was made up, it is expedient to increase the amount of the latter to a degree such that it will allow not only the accepted characteristic of payload as a function of range to be maintained but also the planned cost of transport. An increase in takeoff weight is not always connected with an increase in the weight of the fitted airplane. It also increases as a result of development of the airplane in the process of its planning, which is in conjunction with the natural strivings of the designers to increase economy of the future airplane by means of increasing the load capacity and flight range. It was already noted that

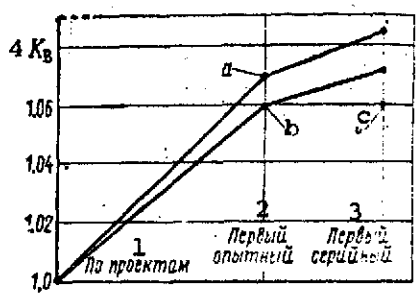

Fig. 3.13. Coefficient of increase of the weight of a fitted airplane (averaged values) during the process of planning, testing and finishing. Average values, located according to materials of: a - work [77]; b - work [79]; c - from authors's analysis.

Key: 1. According to projects; 2. First experimental; 3. First series; 4. K_1

development in creation of an airplane takes many years and conditions change over this period of time. In relation to this, forecasts on the dimensions of the airplane and its passenger seating capacity required for the future are made more precise. The latter is increased insignificantly in cases when reserves in strength and thrust are used or when only flight range is increased, and significantly with an increase in commercial payload. An example of the latter might be six of the most widely used foreign second generation airplanes, in which the average increase in takeoff weight (from the preliminary project to the experimental model) reached 16%. With this, however, engine thrust was also increased. The value for the coefficient considering the change in takeoff weight with the development of the airplane during the planning process might also be found to be similar to the coefficient of fitted airplane weight increase. The value of these coefficients, like the explanation of the regularity of /168 increase, allows not only refinement of the project data but also forecasting of the final weight characteristics and strength possibilities for the airplanes.

During the process of operation, changes occur not only in the weight of the empty airplane, as was already noted, but also in takeoff weight. This is explained by the following: a) development of the airplane for the purpose of increasing economy; b) different changes intended to increase flight safety, ease technical servicing and repairs, improve comfort for passengers and so forth.

12.4. Formula for weight planning. Determining the initial data for selection of dimensions and thrust to weight ratio of a planned airplane and for various calculations has, understandably, exclusive meaning. The first of these data are weight data, since the airplane begins with weight. Consequently, accuracy in the planned weight calculations, like in the aerodynamic ones determining the basic parameters of the airplane, have an essential effect on its effectiveness. The accuracy of weight calculations are effected, as was noted, not so much by perfection of methodology as by lacing knowledge of the project at the stage of pre-drawing study. Limitation in the initial workup also determines the degree of ignorance.

Researchers, analyzing the question of advisability in increasing or decreasing weight characteristics during their initial determination arrive at different conclusions. It is understandable that increasing weight will lead in the final analysis to overweighting of the structure, and an extreme reduction might deprive the airplane of promise for development. Designing for reduced loads as a method of creating an effective construction does not relate to this question -- the text will deal with that later. There is in mind here a tendency in weight calculations connected with insufficient information during the initial stages of planning.

While wing area (S) and engine thrust (R) are selected with consideration for the theoretical weight of the fitted airplane (G^t_{ef}), the probable value of its actual weight (G^a_{ef}) will be $G^a_{ef} = K_i G^t_{ef}$ and the divergence mentioned between the technical and economic characteristics and the planned one will occur. Therefore, the following approach to formulation of weight characteristics for an airplane and initial data for planning should be considered advisable.

1. During selection of S and R from conditions of assigned flight, takeoff and landing characteristics the weight of the fitted airplane with consideration for the coefficient of increase used should be taken as the original one. When the probable value for actual weight of the fitted airplane ($K_i G^t_{ef}$) increases by comparison with the theoretical due to an increase in S and R by the amount ξ:

$$G_{ef} = \xi K_i \cdot G^t_{ef}, \qquad (3.9)$$

where G_{ef} is the projected empty fitted airplane weight. Takeoff /169
increases by an amount less than K_i with $\xi = 1$ (i.e. when S and R are selected without considering K_i) and by an amount greater than K_i when S and R are selected on the basis of $K_i \xi G^t_{ef}$. The amount of takeoff weight increase (K_{i_0}) in this case will depend on the relative weights of the fitted airplane ($\bar{G}_{ef}$) and fuel ($\bar{G}_f$) and is determined by the equation

$$K_{i_0} = 1 + \frac{\bar{G}^t_f (K_i \xi - 1)}{1 - \bar{G}_f} \qquad (3.10)$$

The projected takeoff weight (G_0) is determined by the equation

$$G_0 = \frac{\xi K_i G^t_{ef} + G_{cp}}{1 - \bar{G}_f} \qquad (3.11)$$

where G_{cp} is the weight of the commercial payload.

The amount of the coefficient ξ lies within narrow limits and depends on the values for the relative weights of fitted airplane ($\bar{G}_{ef}$) and fuel ($\bar{G}_f$) and also on conditions of selection of the wing area (in some cases it is selected simultaneously with selection of thrust and in others with conditions of the airplane's planning around existing engines).

The weight characteristics obtained from Eqs. (3.9) and (3.11) should apparently be included in the sketch project and in the technical conditions (or in the contract). They may be guaranteed.

In determining the airplane's dimensions and engine thrust and in supporting the planned values for weight characteristics, the question of considering progress in the development of materials, in technology and in equipment is disputed. A solution to this problem depends, naturally, on the stage of development of the innovation being examined. A project which is insufficiently mastered at the moment of development can be used for development of an airplane and considered during the planning of modifications. For instance, on the L-1011-8 airplane, gradual introduction into series airplanes of "Khayfil" composition material (under license from the Rolls Royce firm) is provided. Attainment of an annual weight reduction of 1% is planned, and over the 1975-1980 period, it will comprise 4536 kg.

2. When determining weight limits (G_ℓ) over initial ones, it is advisable to take the theoretical data of the weight calculation with consideration for the values of S and R finally selected. Then the total weight limit of a fitted airplane will be $G_\ell = \xi G^t_{ef}$. During the process of developing working drawings, the limiting weight is periodically refined (Fig. 3.14) as refined calculation data arrives or partial changes in the airplane project connected with its assembly are introduced. However, it is desirable that the final limit does not exceed the initial one by a value of more than 1.06.

3. When assembling initial data for strength calculations, it /170 is apparently advisable to take as the initial weight data the same ones as for limiting weights or even with some decrease in them. The calculated weight will then be no higher than the initial theoretical weight, but somewhat lower, and will be defined as

$$G_0^{calc} = \frac{0.9K_i \xi G^t_{ef} + G_{cp}}{1 - \bar{G}_f} \qquad (3.12)$$

The method of planning for reduced loads under conditions of static testing for full loads [62] has also not lost its meaning at the present time, when methods of computing for strength have achieved their perfection. The fact of the matter is that

calculated operational loads in actuality have less meaning due to deformation of the structure, but the stresses are redistributed as the result of plasticity in monolithic constructions and flexion deformation. It is well-known that a displacement of the focus occurs as the result of flexion, which increases static and fatigue strength of the structure. Besides this, natural structural reserves always exist, and with this are taken advantage of to a definite degree, and weak places are reinforced. In summary, a structure which is nearly even in strength is created. It is understandable that not all elements of construction can be planned for reduced loads. The most stressed parts or the most load-bearing ones such as, for instance, control components, elements of the wing center section or junction of airplanes parts are computed with definite reserves. In conjunction with this, initial data for the strength calculation can be compiled on the basis of weight calculation data. The selection of a coefficient for reduction ofloads must understandably agree with the fact that the weight of an empty constructed airplane exceeds the theoretical weight by an amount approximately equal to 1.06.[25] /171

The weight of the fitted airplane during the process of planning and development of the working drawings changes constantly. The dynamics of this change is fixed on graphs which are similar to those presented in Fig. 3.14. This graph is distinguished from those examined above in that the curves are constructed according to a large number of points which correspond, for instance, to the weekly results of weight control, while those in Fig. 3.12 and Fig. 3.13 are constructed according to two or three extreme values for these amounts. During the process of weight control, the expected weight of the fitted airplane is refined according to two directions.

1. The weight of that part of the structure whose drawings are completed up to the given stage of development is corrected (stages are defined as the percent of readiness of the drawings on their total volume, see Fig. 3.14).

2. The weight of the remaining part of the structure and the equipment systems is refined on the basis of periodic refinement of initial data. Consequently, at the stage of 10 or 20% preparedness of the drawings, the weight of the fitted airplane is actually forecasted. However, this forecast allows the amount of the possible overweighting to be determined (already at this initial stage).

From the curves examined (see Fig. 3.14), it is evident that: the theoretic weight located on the level of the sketch development of the project (a) and the weight included in the sketch project (b) remain constant. The latter can be changed if technical conditions for planning are changed by the orderer. The weight

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[25] In this case, if the coefficient has not been considered during formulation of the weight characteristics.

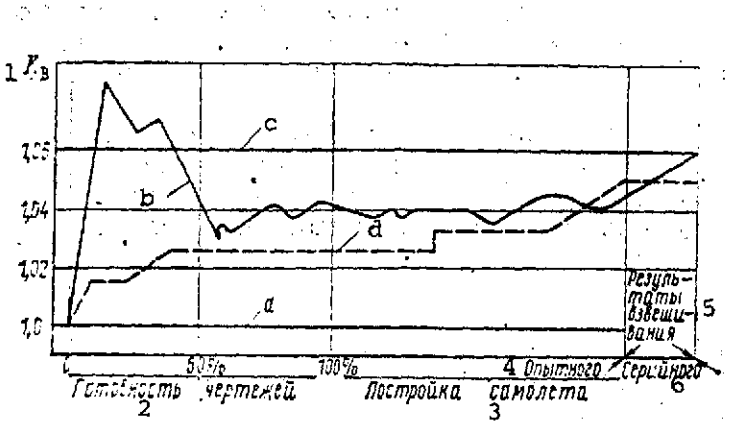

Fig. 3.14. Dynamics of weight characteristic change in the creation process of an airplane: a - theoretic weight; b - weight for sketch project, and contact; c - weight according to drawings (results of weight program fulfillment); d - refined weight limits.

Key: 1. K_i; 2. Readiness of drawings; 3. Construction of the airplane; 4. Experimental; 5. Results of weighing; 6. Series.

according to drawings (c) systematically changes. For the first period of development, it is typical for weight to increase (sometimes even exceeding1.06), and after that, to decrease as the result of the measures taken. The limits are periodically refined (d) as refined loads, technical requirements and so forth appear. The results of weighing the first experimental airplane must be lower than the limit of 1.06, since in the process of its testing and workup of the series drawings, some increase in weight is unavoidable. The weight of the first series airplane must amount to no more than 1.06 of the theoretical and coincide with the description in the technical conditions and in the sketch project.

12.5. An example of determining weight characteristics with consideration for the coefficient of increase. We assume that for a hypothetical airplane with given values for load capacity, cruising, takeoff and landing characteristics, we find: $\bar{R} = 0.265$, $p = 480$ and $\bar{G}_f = 0.35$ and subsequently, the wing area, engine thrust and takeoff weight for two conditions of planning. 1) with $K_i = 1$ (column 2 in Table 3.3) and 2) with $\xi K_i = 1.085$ (column 4). /172
In column 3, the value $K_i = 1.06$ is not a condition for planning. It is the amount of the actual increase in weight or the degree of divergence between the actual weight and the planned. Examination of the example will lead to the following conclusions.

1. The weight of the fitted airplane in the second case (61,000 kg) is only a little greater than the actual weight (59,400 kg), which can be obtained during planning without considering the coefficient 1.06.

2. At the expense of increasing the weight of the fitted airplane by a total of 1600 kg, commercial payload was successfully maintained, while in the opposite case it would have had to be decreased by 3400 kg (by 11%).

3. The value for the load ratio in the second case proves to be higher and the cost of transport lower than the actual values in the case of planning without considering $K_i = 1.06$ (column 3).

4. Comparison of data from the second and fourth columns is not justified, since the first is purely theoretic and practically unreal. If the possibility of their realization is admitted, however, the difference, for instance, in the amount of cost is comparatively small.

TABLE 3.3. EXAMPLE OF DETERMINING WEIGHT CHARACTERISTICS WITH CONSIDERATION AND WITHOUT CONSIDERATION FOR THE COEFFICIENT OF INCREASE

Planning conditions	Without considering the coefficient of increase		With consideration for the coefficient of increase and corresponding selection of S and R	Increase in flight range (fuel reserve) as opposed to assigned	
Character of data and value of coefficients	Project data with $K_i = 1$	Actual data (expected with $K_i = 1.06$	Projected and expected actual data with $\zeta K_i = 1.085$	Projected data $\zeta = 1.03$ $G_f = 1.1 G_f'$	Expected actual data
Weight of fitted airplane in kg	56,000	59,400	61,000	57,600	61,000
Commercial payload in kg	30,000	26,600	30,000	30,000	30,000
Weight of fuel in kg	48,000	48,000	49,000	52,400	49,000
Takeoff weight in kg	134,000	134,000	140,000	140,000	140,000
Load ratio in %	58.2	55.5	56.5	59.0	56.5
Cost in kopeck/ton km	3.56	4.07	3.67	3.62	3.67

It should be noted that the method for forming weight characteristics with consideration for the coefficient 1.06 is not the only one for fulfilling project technical and economic or takeoff and landing data. Another method consists of planning the airplane (i.e., selecting S and R) with conditions of increased flight range against that assigned (and described in the project). Then, the actual increase in projected weight of the fitted airplane must be compensated by a corresponding decrease in fuel (at the expense of the reserve created for this). With this, the takeoff weight, takeoff and landing characteristics and load capacity used in the project will be kept, but the following project data will not be fulfilled: weight of the fitted airplane, maximum landing weight, landing characteristics and cost of shipments. The load ratio will decrease significantly (see Table 3.3, columns 5 and 6). When planning with consideration for the coefficient 1.06, all these, like other project data, are fulfilled. The actual values for weight characteristics in the two latter cases will be identical (see columns 4 and 6). Besides this, the method considering the coefficient 1.06 is also more rigid in relationship to the formulation of initial data for strength calculations. /173

12.6. General conclusions. 1. Coincidence of actual and projected weight of the fitted airplane is possible.

2. Nonagreement cannot serve as a sufficient basis for concluding overweighting of the airplane, if planning was conducted without considering the coefficient of weight increase. There are many different reasons explaining nonagreement, and some of them are progressive (for instance, are connected with an increase in load capacity).

3. Nonagreement can support conclusions on overweighting in those cases when the weight characteristics are formulated by the method presented above (i.e. the actual increase was studied), when the load capacity and range, and also the volume of equipment and technical requirements are not subjected to essential change during the planning process.

4. An increase in takeoff weight as opposed to that projected with a simultaneous increase in specific productivity and with conditions for maintaining the assigned runway class is progressive, if it does not lead to economically unjustified re-sizing of the airplane.

In view of the arguments surrounding this question, it is appropriate also to examine some objections.

1. Is the increase in the weight of the fitted airplane during planning process a "objective regularity" or a "systematic happenstance?" Qualitatively, it is a regularity, of course not without exception. The probability amount is a qualitative expression. The higher degree of innovation, the higher the value for the coefficient of increase.

2. Is the way of introducing the coefficient 1.06 progressive?/174 With respect to creation of structures having minimum weight, of course -- no. It has no relationship to the problem of creating a light structure (the method mentioned of planning for reduced load and others, for instance, relate to this problem). In relation to the overall problem of planning, without a doubt -- yes. It allows attainment of agreement between the actual values of all flying characteristics with those planned and therefore increases the effectiveness of the airplane created.

3. Is a deterioration in weight effectiveness with consideration for the coefficient 1.06 possible. Actually -- no. An increase in weight of the wing and power unit with selection of area and the power-to-weight ratio with consideration for this coefficient will amount to no more than 2.5-3%. This weight increase is also not useless in those exclusive cases when the increase in weight of the fitted airplane does not occur for the reasons examined. Then consideration of the coefficient will lead to an improvement (over the assigned) in flight characteristics and creation of potential for the airplane's development along the line of modification.

4. Is a progressive increase of the value 1.06 G_{ef} by an additional 1.06 possible? From the character of the reasons for this increase, the impossibility of a similar presupposition is absolutely evident (especially if planning was conducted for the reduced loads).

5. Is the coefficient 1.06 an indicator of low precision in weight calculations? The accuracy of calculations depends first of all on the initial data. This coefficient relates not to perfection of the methods, but to precision of the initial data and the dynamics of project development; it is in essence the "coefficient of ignorance" and the "coefficient of careless."

Chapter 13. On Dimensions of the Passenger Airplane

13.1. Meaning of the problem. It is well-known that a modern airplane is a highly complex machine, characterized by a considerable number of different parameters and equipped with a large quantity of different equipment systems. Naturally, therefore, its high effectiveness is created by solution of many scientific and technical problems. One of these, and part of the determining ones, is the problem of the overall dimensions of the airplane. For achievementof high productivity and reduced cost, it is necessary to create airplanes with maximally large dimensions, of course, within the limits of technical possibility at each stage of development and practical necessity for air transport, and with assigned productivity -- minimum dimensions. This is one of the basic rules in planning civilian airplanes. However, a definite dimension connected with the achievement of the maximum effectiveness

corresponds to such a level of development. Airplanes with dimensions greater than the limiting ones have either not been successfully created or were not suitable. True, "premature" airplanes appeared with dimensions exceeding the "very largest" of those in operation. As a rule, they were "airplanes of a single parameter," since other disadvantages were introduced for the sake of dimensions. Such airplanes were distinguished by low loads on the wing, high loads per unit of power, and insufficiently high useful load or low speed. /175

The basic problem in planning is always the problem of dimensions and the weight of the airplane, but during the period of development of wide-fuselage airplanes, it acquired special acuity. It should be noted that the concept of "dimensions" of an airplane includes not only the linear continuation of separate elements and depends not on its area and volume, but includes to an equal degree such characteristics as the mass of the airplane, which to a greater degree determines the dimensions of the airplane and its evolutionary and revolutionary (leaping) changes.

In the process of development of airplanes, their tonnage constantly increased. With the same type of engine, the increase progressed smoothly (Fig. 3.15) and it was tied to improvements in engines and aerodynamics of the airplane. The increase in load ratio, flight range and productivity were a result of this. Development attained a leaping character upon the appearance of new types of engines. The largest leap in airplane dimensions was observed during creation of airbuses. The tonnage of these airplanes on short or medium flights surpassed even the tonnage of the longest range airplanes of the second generation (see Fig. 3.15). /176 Similar conclusions on the character of change in airplane dimensions (tonnage) were obtained during examination of this problem for airplanes of different classes -- short-haul [63] and intercontinental [91]. The quantitative jump in different classes varied, but it is curious that the upper limiting tonnage of airplanes in each of the generation increased by approximately twice. Thus, the Tu-104 and "Comet" jet airplanes had a weight of 70-74 t, second generation airplanes (and modifications of first generation airplanes) -- Il-62, Super VC-10, Boeing 707-320 and DC-8-60 weighed 148-160 t and third generation airplanes -- the Boeing 747 weighs 360 tons. Consequently, for development of passenger airplanes, a growth in tonnage is typical, both with an increase in range and from generation to generation. The latter is connected with an increase in passenger seating capacity and flight speed, which affects the weight of the airplane primarily through the increase in required fuel energy. This leads to the other conclusion, which has an immediate practical significance: each subsequent airplane planned to replace an operational one on the same routes must exceed it in dimensions (tonnage) and usually significantly.

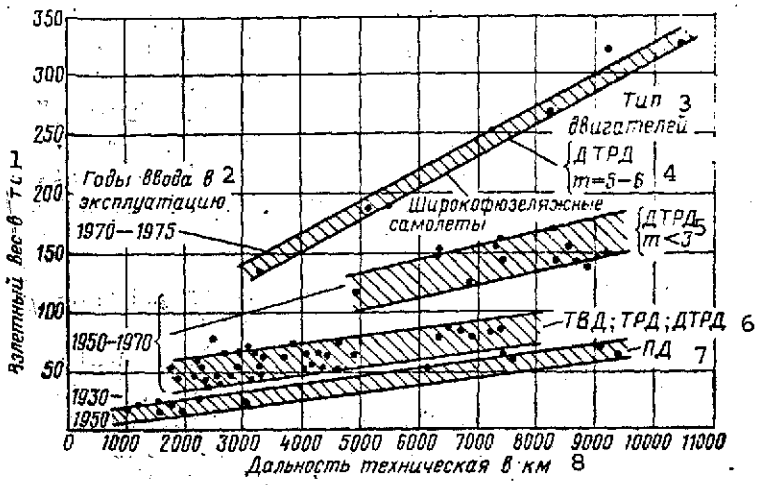

Fig. 3.15. Growth in dimensions (tonnage) of passenger airplanes in the process of their development.

Key: 1. Takeoff weight in t; 2. Years of introduction into operation; 3. Type of engines; 4. Turbofan m = 5-6; 5. Turbofan m < 3; 6. Turboprop, turbojet, turbofan; 7. Piston engine; 8. Technical range in km

During the piston aviation period, an increase in dimensions was blocked by power unit possibilities. With the development of engines and perfection of aerodynamics, the limit in the overall dimensions of an airplane was displaced toward higher tonnage, and the appearance of turbofan engines with a high degree of by-pass finally removed these limitations, which explains the sharp change in slant of the lines corresponding to wide-fuselage airplanes (see Fig. 3.15). One of the indices of engine development leading to an increase effectiveness of airplanes with an increase in their dimensions is the systematic decrease in relative weight of the power units (Fig. 3.16).

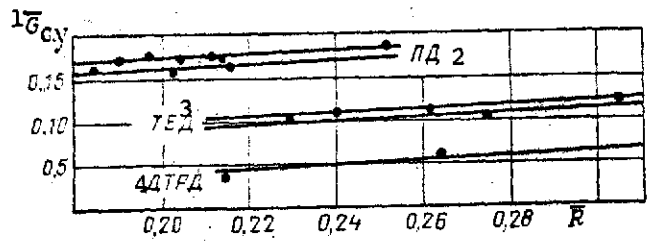

Fig. 3.16. Change in relative power unit weight depending on power-to-weight ratio of the airplanes in the process of their development.

Key: 1. $\bar{G}_{pu}$; 2. Piston engines; 3. Turboprop engines; 4. Turbofan engines

During solution of the /177 problem of an increase in thrust in one engine, the problem of dimensions began to be solved on the basis of forecasts of increased movement. Retention and further reduction in the relative weight of the structure with an increase in tonnage of the airplane (i.e. overcoming the "weight barrier" became the basic problem. In this manner, a sequential increase in the dimensions of the airplane necessary for development of passenger aviation was connected with the weight

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problem, and the lower the calculated flight range, the more complex was its solution. It was exactly because of this that it acquired special meaning for airbuses -- airplanes with high load capacity and relatively low flight range.

An increase in the geometric parameters and tonnage of airplanes will lead, as was noted, to a change in the weight relationships in the total weight balance of the airplane. Concerning flying, takeoff and landing characteristics, they can be changed (especially upon changing the length of the flight) or retained unchanged. All this depends on formulation of the problem and results of technical and economic studies. It is understandable that selection of the dimensions of an airplane is connected with the character of air routes and the increase in demand, but it also an essential effect on development of air transport. Thus, for instance, the dimensions of the Douglas DC-3 airplane, which was remarkable in all respects but created for American lines, was accepted in its own time in Europe, and this could not help but be reflected on the further development of civilian aviation. All-encompassing study has now supported the fact that airplanes of smaller dimensions are actually required for European routes than for American ones.

13.2. Parameters of the overal dimenions of the passenger airplane. For evaluation of the effect of airplane dimensions on its transport and economic effectiveness, it is necessary to establish what parameters of the airplane characterize its overall dimensions to the greatest degree. It was already noted that the weight of the airplane is the most objective of its criteria, in particular because during the process of its development, it increases more rapidly than the geometric dimensions of the airplane. Thus, during the period from 1900 to 1970 (i.e. beginning with the "flier") wing span increased by 6 times, its area by 12 times and takeoff weight by 1000 times, since the specific loading on the wing increased by almost 100 times. Consequently, the weight characteristic -- the takeoff weight and the weight of the empty fitted airplane -- is a value which is most sensitive to all changes occurring in the airplane and affects all flying, takeoff and landing characteristics of the airplane to the greatest degree.

Wing span, which is also taken as a parameter of airplane dimensions, is a more stable value. It has practically not changed over the course of an extended period of time, and it therefore less suitable for this purpose, although dependencies of a graphical type are presented in Fig. 3.17, and represent some interest. They are used to illustrate the increase in effectiveness. /178

The takeoff weight of an airplane in conjunction with the basic parameters (p, $\bar{R}$) allows the tendency for change in the airplane's dimensions and many of its characteristics, as well as different types of its effectiveness to be studied.

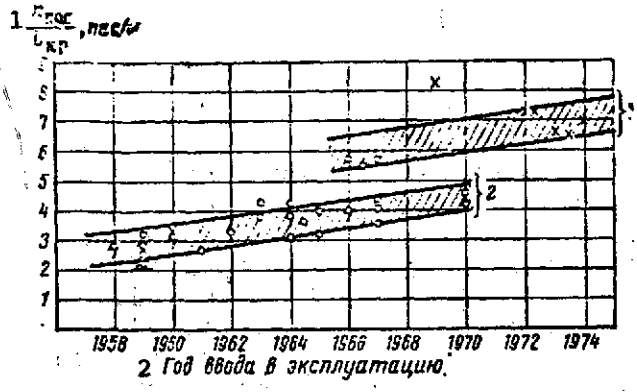

Fig. 3.17. Increase in effectiveness of dimensions: 1 - modifications with changed fuselages and airbuses; 2 - initial variations and modifications with moderate increase in the number of passengers; o - initial variation and modifications; x - airbuses.

Key: 1. n_{pax}/ℓ_{cr}, pax/km; 2. Year of introduction into operation.

Another characteristics -- the weight of the fitted airplane -- is used in many cases. For instance, together with the same parameters, it allows study to be made of the level of weight perfection of the structure. In economic analyses the cost of the airplane, with sufficient approximation, is taken as proportional to the weight of the fitted airplane. The weight of the empty airplane is used as a dimension parameter during determination of the labor consumption and required production capabilities and areas, and in other cases.

13.3. The effect of airplane dimensions on its transport effectiveness. Problems of transport effectiveness for passenger airplanes with gas turbine engines of the first two generations and for projected large-dimensioned airplanes were analyzed in works [40, 62 and 91]. With this, productivity of the airplane and, in particular, its productive return, were used as the basic criteria of transport effectiveness. The larger the dimensions of the airplane, naturally, the greater its productivity. However, during solution of the problem of airplane dimensions, specific loading on the wing plays an essential role in achieving maximum effectiveness. The fact of the matter is that with an increase in structure dimensions, its weight increases more rapidly than its strength. In airplane construction, this regularity does not appear the same as in other /179 areas of technology, due to the simultaneous increase in specific loading. The latter promotes a fuller utilization of the mechanical properties of the materials and an increase in the level of stresses in structures of airplanes having large dimensions. Progress in metallurgy and technology also promote this. As the result of an increase in an airplane's dimension, the relative weight of the structure decreases. An increase in specific loading on the wing (Fig. 3.18) was connected with the fact that up to recent times, flight range also increased in conformity with an increase in dimensions of the airplane. This in turn eliminated or alleviated the rigid requirements for takeoff and landing characteristics. Difficulty in achievement of a relatively low fitted airplane weight for the short-haul A-300 airbus was also partially connected with a low specific loading on the wing, which was limited by a relatively short runway length.

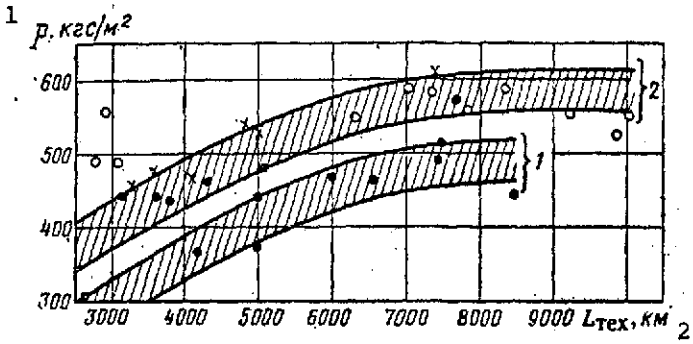

Fig. 3.18. Specific loading on the wing: 1 - airplanes of the first generation (•); 2. airplanes of the second generation and their modifications (o); and airbuses (x).

Key: 1. p, kg/m^2; 2. L_{tech}, km

In this way, high transport effectiveness, determined by productivity and weight perfection, is achieved by high value for takeoff weight with a low relative weight of the empty airplane. The connection between these values can be expressed through a dependency of the specific loading on the weight of the fitted airplane ($P_{ef} = G_{ef}/S$) and on the takeoff specific loading ($P_0 = G_0/S$) on the wing. In this place, airplanes are grouped according to zones corresponding to their power-to-weight ratios (Fig. 3.19), which also has a significant effect on the weight of the fitted airplane. An independent group of modifications possessing high weight effectiveness is also separated out. Airbuses, in accordance with regularities (see Figs. 3.2 and 3.3) form a group distinguished by its high values for p_{ef}.

A measure of the increase in flight length productivity with the increase in airplane dimensions in its absolute value is illustrated by the graph in Fig. 3.20. From examination it is /180 evident that the productivity of large-dimensioned airplanes (airbuses) becomes comparable with the productivity of airplanes having a significantly greater range. With this, the productivity of airplanes increases more rapidly than does takeoff weight. These conclusions are supported with great evidence by the dependency curves of the parameter of passenger airplane transport effectiveness on takeoff weight, which represents a productive return and is expressed by the relationship $G_{cp}L/G_0$. During its computation, the following are taken as initial data: the maximum commercial payload weight (but no more than 120-125 n_{pax}) and maximum range (practical /181 or technical), achievable on flights with this load and using maximum takeoff weight. It should be noted that the use of the parameter of productive return not by flight length, but by the hour can, as shown in work [62] lead to erroneous results.

An increase in productive return of large-dimensioned airplanes occurs primarily due to a sharp increase in commercial payload and a significant decrease in the required fuel reserve and high economy of new engines (the numerator increases as the result of the first and the second decreases the denominator). The degree of decrease in fuel consumption per unit of productivity $G_f/G_{cp}L$ is illustrated in Fig. 3.21, where not only the specific fuel consumption but the total kilometric consumption which also depends

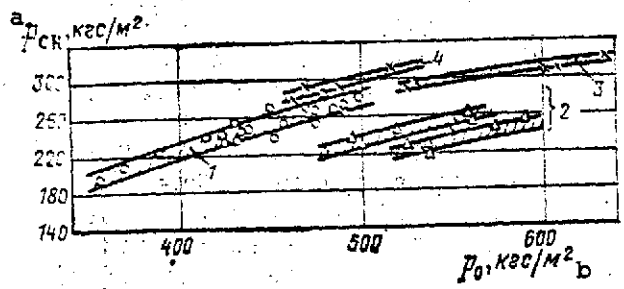

Fig. 3.19. Change in specific loading on the wing from the weight of the fitted airplane in dependency on the takeoff specific load and power-to-weight ratio: 1 - $\bar{R}$ = 0.24-0.3; 2 - $\bar{R}$ = 0.2-0.28 (modifications); 3 - $\bar{R}$ = 0.25-0.3 (airbuses); n_e = 3 and 4; and 4 - $\bar{R}$ = 0.32-0.37 (airbuses), n_e = 2.

Key: a. p_f, kg/m^2; b. p_0, kg/m^2

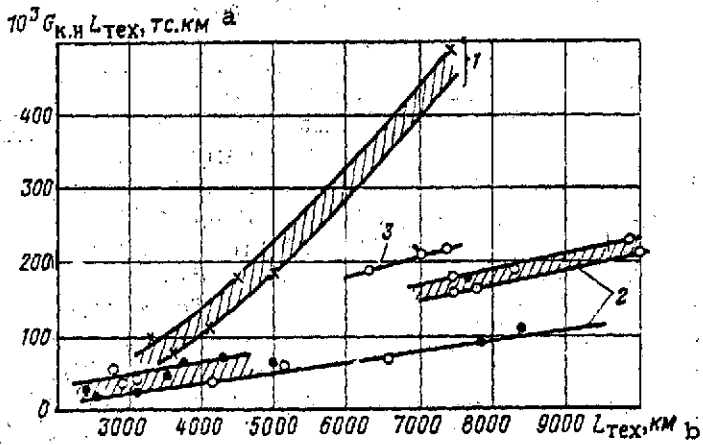

Fig. 3.20. Change in productivity of passenger airplanes according to flight range: 1 - airbuses (x); 2 - airplanes (•) and their modifications (o) of the first and second generations; 3 - modifications for 250 seats.

Key: a. $10^3 G_{cp} L_{tech}$, thousand km; b. L_{tech}, km

aerodynamic qualities and the weight of the fitted airplane are considered. As the result of this, the given parameter is relatively objective.

Besides productive return, such weight parameters as the relationship of fitted airplane weight to its productivity (see Fig. 3.6) and to the maximum number of passengers (see Fig. 3.7), examined above, can also serve as parameters of transport effectiveness. If the cost proportional to the weight of the fitted airplane is used, their relationship can serve as a parameter of economic effectiveness. Examination of the graphs mentioned supports the conclusions made above: large-dimensioned airplanes which are not distinguished by high weight perfection (in which the growth in dimensions was expected to be greater), possess a high transport effectiveness. The weight of the fitted airplane attributable to one passenger and to a unit of productivity in large-dimensioned airplanes is less than in preceding airplanes of the same class, which also promotes an increase in this effectiveness.

13.4. Geometric relationships. The dimensions of an airplane, besides the specific loading on the wing (whose increase will lead to a decrease in area of the wing and empennage), /182 depends on the degree of utilization of fuselage space or density of

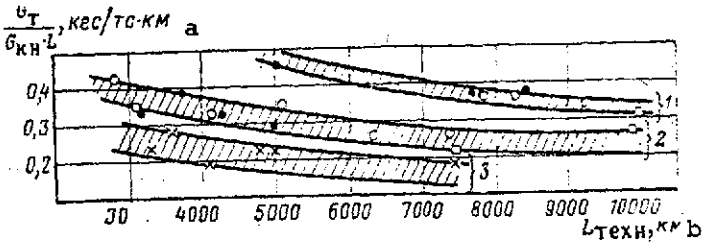

Fig. 3.21. Fuel consumption per unit of productivity of airplanes (•) of the first (1) and second (2) generations, their modifications (o) and airbuses (3).

Key: a. $G_f/G_{cp}L$, kg/thousand km; b. Ltech, km

arrangement. With an increase in the latter, naturally, dimensions of the fuselage and the relative weight of the empty airplane are decreased and its transport effectiveness increases. Relatively strict dependencies of the weight of the fitted airplane on the area of the wetted surface of the airplane (see Fig. 3.8) and its volume exist. Thus, if we examine the weight of the fitted airplane relative to the volume of the wing (V_w) and the fuselage (V_f) then it is possible to find that with an increase in airplane dimensions, this value increases insignificantly, and the weight of the airplane in relation to its surface (see Fig. 3.8) increases to a greater degree. To determine the volume of the airplane, the following approximate formula can be used

$$V_w + V_f = \left(\frac{\sum S_{wet}}{4.83 K_{V\Sigma}}\right)^{3.2},$$

where $K_{V\Sigma}$ -- coefficient of form [62].

The geometric relationships of high-tonnage airplanes, regardless of the significant increase in fuselage diameter, have almost not changed. This can be explained with two reasons. In the first place, a definite correlation between the diameter and length of the fuselage was maintained, and in the second, the values for specific loading on the wing were almost unchanged. In the past, these dependencies were also extremely stable, with the exception of modifications with stretched fuselages, in which λ_f reached 15. Fig. 3.22 presents the dependency between dimensions of the wing, fuselage and passenger seating capacity of an airplane. It is also easy to note the stability of geometric relationships of airplanes with an increase in passenger seating capacity. With this, it should be kept in mind that the range of specific loads on the wing in the given airplanes lies within a narrow band (450-520 kg/m^2) with the exception of the Boeing 747 airplane.

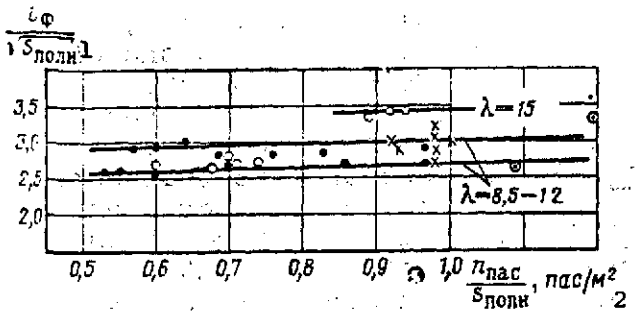

Fig. 3.22. Change in the relative length of the fuselage according to increase in passenger seating capacity of airplanes: ● - initial variation; o - modifications; x - airbuses.

Key: 1. $l_f/\sqrt{S_{total}}$; 2. n_{pax}/S_{total}, pax/m^2

The parameter n_{pax}/S /183 does not have a strict dependency on specific loading on the wing. With the same value it can both increase and decrease. But with an increase in it, i.e. with an increase in passenger seating capacity, the relative length of the fuselage will increase without fail and with a relatively strict conformity. This situation must be considered in weight and economic analyses of large-dimensioned airplanes, especially in cases where their comparison with airplanes which are typical for the first two generations is conducted. Other dependencies which will immediately express the geometric relationship will lead to similar conclusions. Concerning the space relationships between different compartments, they are examined in Chapter 7, which is devoted to dimensions and configuration of the fuselage in modern passenger airplanes, as well as density of passenger cabin arrangement.

The relationship between geometric parameters of the wing and the empennage continues to be used with a steady tendency towards increasing the relative area of the empennage (for more detail see 15.4).

PART 4. PECULIARITIES IN PLANNING AIRPLANES WITH TAIL MOUNTING OF THE ENGINES /184

Chapter 14. Advantages and Disadvantages

14.1. The problem of grouping engines on airplanes. The grouping of power units was relatively the same with piston and turboprop engines. On airplanes with a single piston engine, it was installed in the nose part of the fuselage, and with the number of engines at two or more, in front of the wing. Installation behind the wing (with pusher propellers) is not encountered on passenger airplanes. Turboprop engines are installed only in front of the wing. The problem of mounting engines on the airplane arose after the creation of turbojets and became more acute upon the appearance of turbofans with a high degree of by-pass.

Power units of the first generation of airplanes with gas turbine engines were distinguished by their multiplicity of form both in engine types (turboprop, turbojet, turbofan), and in the types of their placement (built into the wing, on pylons beneath the wing, on the tail of the fuselage). For the second generation of passenger airplanes, singularity in both factors was characteristic -- turbofan engines and the latter of the described grouping predominated. In the third generation, a new type of engines appeared and they returned to their placement beneath the wings (EbW). The fact of the matter is that many well-known advantages of engine placement on the fuselage (EoF) on the new type of airplane turned out to be lost and the disadvantage, although to a lesser degree, were retained. A new (compromise) type of arrangement appeared -- two engines beneath the wing, one on the tail.

Doubt as to the advantages of the EoF were first expressed by the Boeing firm. Having created the 727 airplane according to this layout, they dropped it during development of the Boeing 737. This solution was apparently affected by many reasons, among which were the VC-10 airplane, unsuccessful in the first stage, which at first led to the unprecedented situation concerning the company's intentions to liquidate orders for the airplanes when part of them were already finished. The situation was aggravated by the fact that measures for increasing commercial payload to compensate overweighting of the structure were not taken in time. During creation of a four-engine airplane with EoF, a whole series of extremely complex problems actually arose, and it is not surprising that the Vickers firm was not successful in finding the optimum solutions and avoiding some cost overruns. Even the Boeing 727 in its initial variation was not as well perfected as was its predecessor, the Boeing 707. A later modification, the Boeing 727-200 proved to be very promising and uncovered large reserves which were built in during creation of this type of airplane. In the final analysis, both airplanes (VC-10 and Boeing 727), as will be shown below, totally rehabilitated the then-new layout. Later, the Boeing 747s and airbuses brought the advantages of the EoF layout applied /185

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to heavy airplanes under doubt, however the Yak-40, Fokker F-28, Lockheed "Jet Star" and large number of smaller airplanes successfully supported the advantages of this configuration for themselves. Dropping the EoF layout in the A-300 airbus project was motivated by more complex access to the engines, the necessity for a wide center of gravity envelope representing freedom during loading, consideration for the problem of the superstall and, finally, by promise for lengthening the fuselage, which is more easily realized with the EbW configuration. However, in the project of another European airbus (BAC 3.11) the EoF layout was again used, and the fact that the variation with EoF was again examined during the project for the Boeing 767 airplane speaks once more of the disputed character of this layout.

The very fact of such a prolonged argument can be explained in part by the fact that some advantages of the EoF layout allow only a qualitative evaluation while others, although allowing quantitative evaluation are difficult to determine. At the same time, a quantitative evaluation can be made of its inherent deficiencies.

It is interesting that both the argument and research continue, and the number of airplanes built with EoF over a 6-year period (1965-1970) is almost equal to the number of airplanes with EbW built over a 13-year period (1958-1970).

During planning of airplanes with EbW, searches are being conducted for solutions which would combine all advantages of the two configurations. It is not yet clear whether the EoF configuration will increase in the future or totally pass into history. It is still unclear because, on one hand, the installation of four engines with a high degree of by-pass on the tail of the fuselage is practically impossible, and on the other, increasing the degree of by-pass to 10 or greater allows creation of engines with unlimited high thrust and supports the tendency towards decreasing the number of engines to three or two. This, in its turn, like the very large diameter of these engines, will accompany the development of the tail mounting. Another solution, true, is possible. The high-wing layout, interesting in many respects but rarely used for passenger airplanes in the past, allows the fastening of large diameter engines beneath the wing without weight losses. True, /186 solving the safety problems is more complex with this configuration.

Grouping of engines on an airplane affects its aerodynamics, stability and controllability, safety and comfort, operational properties and economics, strength and weight, overall arrangement, center of gravity and geometric parameters. This effect on second generation airplanes is analyzed below. Peculiarities in the tail arrangement of engines on wide-fuselage airplanes (airbuses) are examined separately in Chapter 16.

14.2. Problems of aerodynamics. The EoF placement leads to an aerodynamically "clean" wing with a high critical M number; decreases resistance of the pods and that of the airplane as a

whole (Fig. 4.1) and creates the possibility for mechanizing the wing along its entire span with better conditions for ground effect and, consequently, it increases the coefficient of lift force on takeoff and landing. As a result, airplanes with EoF and a landing weight equal to that of equivalent airplanes with EbW can have a lower speed for approach to a landing (V_{al}) and with a set V_{al}, the permissible landing weight (G_{ldg}) can be noticeably higher (Fig. 4.2[1]). This improves economics, since the necessity for refueling at intermediate airports is eliminated, which decreases standing time and increases turnaround.

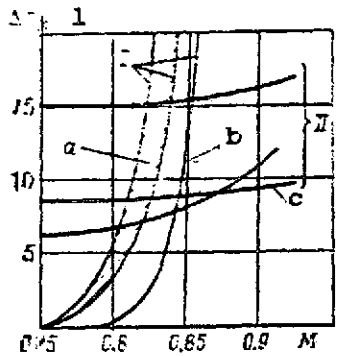

Fig. 4.1. Increase in resistance of gondolas (I) and the airplane (II) with groupings: a - EbW; b - EoF; c - built into the wing. According to materials of "The Aeroplane," No. 2509, November 20, 1959, p. 507.

Key: 1. Δc_x, %

Airplane aerodynamics connected with engine configuration include: problems of interference from the engine pods and fuselage, the work of air intakes at high angles of attack, reasons for the formation of disturbances causing loss in thrust and others. The solution of these, as with all problems of local aerodynamics, depends on many conditions, and the evaluation of these two configurations has an actual character. For instance, the mutual effect of the pods and the wing (with EbW) is connected with the amount of their extension in front of the wing, and that of the pod and fuselage (with EoF) depends on the angle of pod installation, shape of the faring and so forth. The most complex problems are connected with loss of effectiveness of the /187 T-shaped empennage during superstall at higher than critical angles of attack. Shadowing of the empennage in this case is increased by the engine pods (with EoF). Problems of stability are solved with either aerodynamic arrangement of the wing (as on the Il-62) or with a significant increase in areas and λ of the empennage (as on the BAC 1.11).

14.3. Safety, cabin arrangement and comfort, operation and economics. Removal of the engines from the fuel decreases the possibility of its ignition upon the appearance of a fire, especially during a gear-up landing. Damage to the engines in this situation and damage to the hermetic seal of the cabin upon destruction of an

[1] The unusual linearity of this dependency can be explained by the low increase, within limits of which the following equation is true:

$$V_{al_1} = V_{al_2}\sqrt{\frac{G_{ldg1}}{G_{ldg2}}} = V_{al_2}\sqrt{1+\frac{\Delta G}{G_{ldg2}}} = V_{al_2}\left(1+0.5\frac{\Delta G}{G_{ldg2}}\right).$$

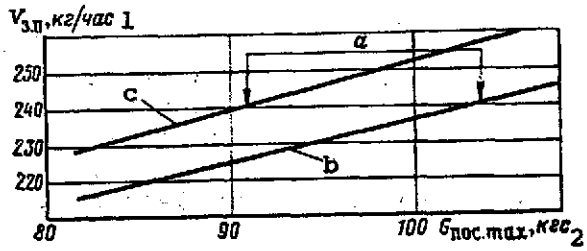

Fig. 4.2. Increase in the landing weight with a constant speed for approach to the landing (a). Airplanes with EoF (b) and with EbW (c). With conditions S = = const for each of the airplanes.
According to materials of "The Aeroplane," No. 2549, August 26, 1960, p. 242.

Key: 1. V_{al}, km/h; 2. $G_{ldg\ max}$, kg

engine compressor in flight are eliminated. Then, the floating characteristics are increased in a case of a forced landing on water. Danger of striking the pods on the ground while in a bank during a crosswing takeoff or landing, and also when taxiing across uneven ground is eliminated. No less essential is the fact that the air intakes are removed from the ground, which decreases the possibility of dirt and other matter entering them. Danger of the appearance of fatigue damage from acoustical loads is also decreased, since in this case, only the tail portion of the fuselage and part of the empennage is subjected to their action.

Arrangement of the cabin also depends on location of the engines, which has a definite effect on location of the entry doors and location of the seats and auxiliary compartments connected with this. For fuselages with a relatively low number of seats (airplanes of the Tu-134, BAC 1.11, DC-9, Boeing 737 and "Mercury" type) EoF installation will lead to a less advantageous arrangement of thecabin due to the extreme rear location of the wing. (Definite requirements for door location can also be hindered by the EoF configuration.) With large fuselage length (over 50 m) the tail mounting, on the contrary, accompanies a more even placement of the three doors and creation of three equal-sized cabins of optimum dimensions. /188

Comfort is to a significant degree determined by the level of noise in the cabin, which fatigues and irritates the passenger. When the source of the noise is located on the wing, the noise level is somewhat decreased, so that in the front cabin it is almost not heard. One of the serious requirements for operation is the decrease in the level of noise around airports. With the EbW location, the duration of the noise action is increased, since the wing is a form of noise reflector and amplifier. The EoF location decreases the duration of noise. With the EbW configuration, noise reducing pods must be created.

Operation of airplanes and, in particular, servicing of the engines at the airport is simplified with the EoF arrangement, and their removal from the ground decreases danger for service personnel (ture, access is somewhat deteriorated). Location of entry

doors which are closer to the ground than on airplanes with EbW is another operational advantage.

Economics of an airplane with EoF location somewhat decreases, which is connected with weight losses (due to achievement of the listed advantages) and an increase, as the result of that, in the initial cost of the airplane. However, this is compensated by an attractive feature due to the increased comfort and safety of a larger number of passengers, i.e. an increase in the coefficient of passenger loading (Fig. 4.3). A multitude of information shows that on routes where two types of airplanes, for instance, the Super VC-10 (with EoF) and the Boeing 707 (with EbW) are operated simultaneously, the coefficient of passenger loading of the first is inevitably higher by 12-20%.[2] On the North Atlantic (highest loaded)/189 routes, the average coefficient of loading of the world's airplane fleet during the period 1965-1969 comprised 0.59, and the BOAC aviation company (of the Super VC-10 airplane) achieved 0.65.[3] This compensates for the higher direct operational expenses than in the Boeing 707. The cost of an airplane-hour in the first is 1116.4 dollars, as opposed to 1010.4 in the second, whic is explained primarily by high weight of the empty airplane.

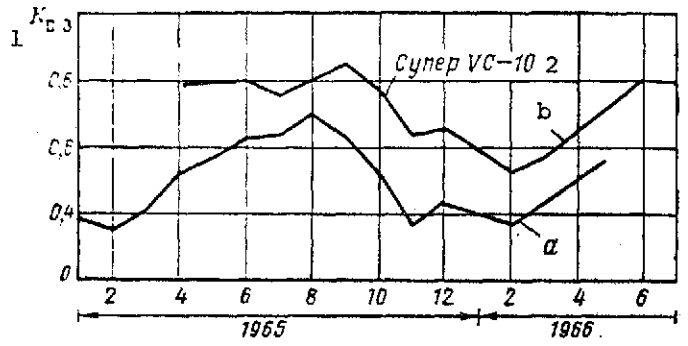

Fig. 4.3. Typical relationship of coefficients of passenger loading of airplanes with EbW (a) and EoF (b).

Key: 1. K_{pl}; 2. Super VC-10

14.4. Problems of weight. The primary deficiency in the layout with EoF is the unavoidable weighting of the structure, which, however, can be brought down to a value which to a definite degree is compensated for by the descreased resistance in cruise configuration and improved landing characteristics. How great these layout weight losses are, whether or not their relative values are the same for airplanes of different tonnage and what part of them are compensated by the advantages acquired -- all these questions are the subject of a rather complex analysis.

The increase in the weight of the structure (by comparison with an equivalent airplane with EbW) occurs not only as the result

[2] Flight, September 15, 1966.

[3] Flight, February 26, 1970.

of an increase in the weight of the still-loaded wing and the fuselage, burdened with engines, but also as the result of less effective utilization of the space in the tail part of the fuselage, and also as the result of arrangement peculiarities of the airplane. In the area of the engines, the fuselage is not used for placement of passenger seats, and with a set number of seats, in many cases it has a great length. The necessity for additional insert in the area of the engines and its dimensions depends on the overall length of the fuselage. The fact of the matter is that there is almost no difference in the cross-sectional dimensions of large (160 t) and medium (60 t) airplanes. Therefore, the length of the tail portion, defined by aerodymically advantageous outlines, in short fuselages is relatively longer, and the requirement for its increase (in cases of EoF) is less. The total increase in the flexion moments in the sections around the tail portion increases by 15-30%, regardless of the fact that its length (to the wing) is decreased as the result of displacement of the wing due to conditions of centering. With this, the proportion of load from the power unit (with consideration for air loads on the pods) in total flexion moment reaches 25-30%. True, only the weight of the longitudinal members of the tail portion, which comprises less than 20% of the weight of the fuselage is increased because of the increase in this moment. Loads on the nose portion also increase as the result of the significant shift of the wing backward from conditions of centering.

The weight of the fuselage increases and as a result, the elements of its connection with the vertical stabilizer (which absorbs great loads with a T-shaped empennage) and with the not-unloaded wing (which absorbs great flexion moment in this case) are made heavier. The weight of the wing also increases as a result of several reasons. The second is the increase in flap area in cases where this is possible (see Fig. 14.2). Also, if the flap is made according to the three-piece layout, the increase in weight is significant but effective. The empennage is made somewhat heavier (for reasons see in 15.4), and with four engines, the pods are made significantly heavier, by 35-40% [62]. With two engines, they are practically equal. It should be noted that power units with three engines located on the tail and those with their mixed placement (two on the wing, and the third on the tail) are also equal in a weight relationship. /190

Some peculiarities of the EoF layout lead to compensation of the weight losses. It is known, for instance, that gear height is determined by landing angle (α_{ldg}), the length of the tail portion (ℓ_{tp}) of the fuselage (Fig. 4.4) and the required clearance between the engines and the ground (Fig. 4.5). With equal α_{ldg}, the weight ofthe legs must be lighter with EoF arrangement. In actuality, on airplanes of the second generation this did not happen. As a result of a large c_y of the more highly mechanized wings, α_{ldg} was increased in airplanes with EoF and the height and weight of the gear legs did not decrease. In this case, however, a new capability

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was obtained, which is also not excluded for airplanes with EbW. Nevertheless, with equal mechanization of the wing in equivalent airplanes, the uprights are still lighter (in an analysis, the results of which are presented below, the conditions $\alpha'_{ldg} = \alpha''_{ldg}$ are used in accordance with this).

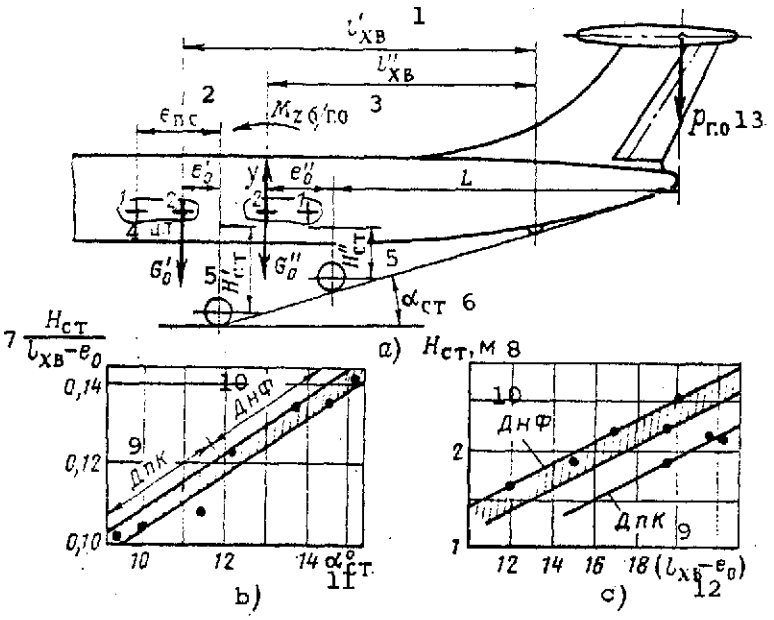

Fig. 4.4. Parameters of airplane gear with different engine arrangement and diagram of acting forces at the moment of rotation (a), the relative (b) and absolute (c) values for gear legs.

Key: 1. ℓ_{tail}; 2. e_{ef}; 3. M_z b/hs; 4. CG; 5. H_{leg}; 6. α_{leg}; 7. $H_{leg}/(\ell_{leg} - e_0)$; 8. H_{leg}, m; 9. EbW; 10. EoF; 11. $\alpha°_{leg}$; 12. $(\ell_{tail} - e_0)$; 13. P_{hs}

When determining the schematic weight losses, wings, equivalent with respect to takeoff and landing characteristics (see Fig. 4.2) should also be examined, i.e. an increase in the degree of mechanization with EoF will conditionally compensate for the increase in wing area with EbW. The weight equivalent can be found from the equation connecting wing area (S) with velocity of approach to a landing (V_{al}). $S'' = S'(V'_v/V''_{al})^2$. Here the values noted with one stripe relate to airplanes with EbW and those with two relate to airplanes with EoF. This equation is true for cases in which wing area is determined by the landing configuration and not that of takeoff. The latter is now encountered ever more rarely as the result of an increase in landing weight (up to

0.9-0.95 of takeoff weight) and extensive mechanization of the wing, and also with the two-engine layout of the airplane. The weight equivalent of improving the cruise characteristics (see Fig. 4.1) can be found through the change in required fuel reserve. If we assume that c_x decreases by 3%, and the cruise number M with this increases by 0.03, then with other conditions being equal, it is not difficult to find the value for a decrease in fuel weight. From this it follows that schematic weight expenditures cannot be seen as free losses. One part of them is compensated by an improvement in the takeoff and landing characteristics, another with a decrease in fuel reserves, and a third with an increase in comfort and safety, which leads to an increase in the degree of utilization of the available number of seats. All this in the final analysis will increase the economic effectiveness of the airplane.

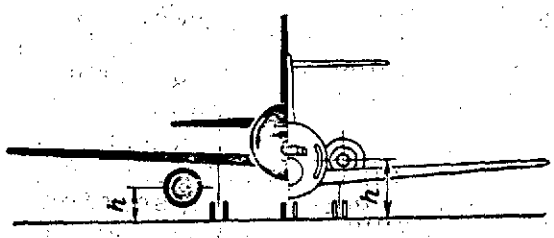

Fig. 4.5. Location of engines beneath the wing and on the fuselage.

The reasons for weighting and the achievable advantages turned out to be less disputed than the amount of qualitative evaluation. We recall that the relative amount of weighting is evaluated differently by different authors. They assert, for instance, that for the "Trident" airplane it comprises 4%, for the "Super" VC-10, 3.5-4% (and, consequently, it coincides in airplanes with very different tonnage). Others count it as equal to 5-10%. Still others propose that the /192 effect of a weight change is better felt on a four-engine airplane than on a two-engine one. It is easy to agree with the latter, keeping in mind that for the time being the two-engine layout is satisfactorily used only on airplanes of limited tonnage (see Chapter 7). The reasons for the difference in view can be sought in the different approach to research, in consideration for a different number of factors, in the accuracy of determining the minimum structural weight satisfying strength requirements and so forth.

Our investigations showed that the relative amount of weighting due to layout increases in conformity with an increase in takeoff weight. We allowed construction of an approximation dependency (Fig. 4.6) for three initial conditions: 1) without recalculating characteristics; 2) with recalculation on the basis of the equivalence indicated above; 3) with consideration for the development of an airplane layout with EoF, examined below. The unusual ap- /193 pearance of this conformity[4] can be explained by the following.

[4] A conformity of the type $\bar{G}_1 = f(G_0)$ usually has an opposite slant of the lines (where $\bar{G}_1$ is the relative weight of the parts of the airplane and its components.

A significant part of the schematic weighting belongs to the fuselage, and its structure in large airplanes is more loaded, i.e. the level of stress is higher. In airplanes of, for instance, medium tonnage because of conditions of rigidity and structural requirements, stresses turn out to be lower. As a result of this, an increase in load on the fuselage (with EoF) in short-haul and medium-haul airplanes will require less additional metal. These fuselages can to some degree be preloaded, increasing stresses. A second reason for the unusual slant of the line is the regular decrease in the number of engines with a decrease in airplane tonnage. Weight expenditures with two or three engines are less than with four, primarily due to weight of the pods. The weight of fastening one engine on each side of the fuselage is practically the same as the weight of fastening them beneath the wing, and fastening two engines on each side is approximately half again heavier.

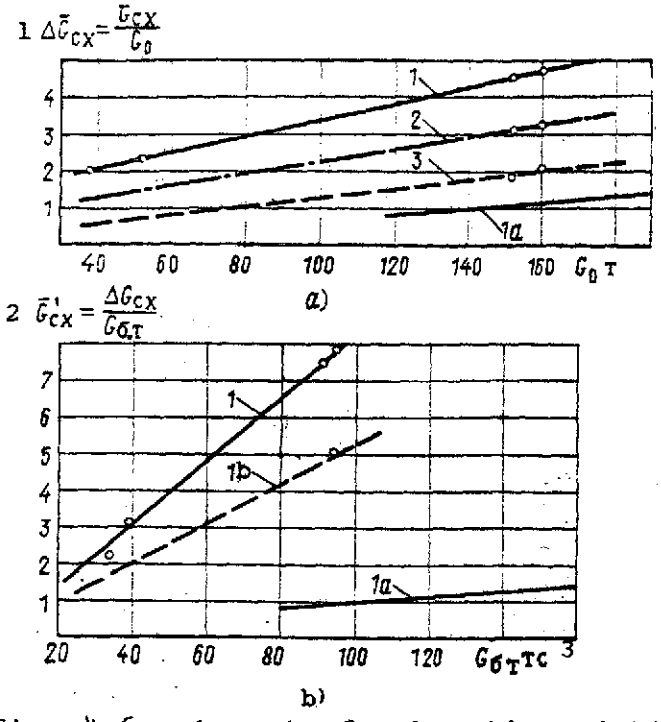

Fig. 4.6. Amount of schematic weighting relative to takeoff weight (a) and zero fuel weight of an airplane (b). Airplanes with three-leg (1) and four-leg (1b) gear. With recalculation of the takeoff and landing (2), and also the cruise (3) characteristics. Airbuses without recalculation of characteristics (1a).

Key: a. $\Delta\bar{G}_{sch} = G_{sch}/G_0$; 2. $\bar{G}'_{sch} = \Delta G_{sch}/G_{zf}$; 3. G_{zf}, t

The less disputed character of the EoF configuration on low-tonnage airplanes is explained by the lesser amount of schematic weighting (see Fig. 4.6), a higher commercial load ratio (see Fig. 3.1), a lower value for the coefficient of takeoff weight increase and, in the final analysis, lower economic expenditures.

Chapter 15. Grouping Schematics and Centering of the Airplane

15.1. Types of grouping schematics.

Tail grouping of the power units, which influences the many problems of grouping in the airplane, passenger cabins and equipment, was first accomplished on the two-engine "Caravelle" airplane. After that, the four-engine VC-10, Il-62 and three-engine airplanes ("Trident," Boeing 727, Tu-154 and Yak-40) appeared. A large number of airplanes with two

engines for short lines (BAC 1.11, DC-9, Tu-134, F-28) and local lines as well as airplanes for service purposes were later created.

The two- and four-engine schematics, differing from the three-engine ones, are identical in type. They are characterized by the position of the engines relative to the wing (a and h on Fig. 4.7), bringing about the necessity for a definite correlationship between the root chord of the wing, fuselage diameter and position of the engines. This mutual position must exclude the possibility of stalling at the air intake entrances, especially at high angles of attack, and the phenomenon of engine pumping. We recall that condi- /194
tions for EbW installation have a different character. Here the problems of directional control, clearance from the ground, location of flaps and unloading of the wing are solved. In this, it is considered that savings in the weight of the wing with an increase in engine speeding is reduced with the increase in the weight of the vertical stabilizer, whose area must be increased out of conditions for providing longitudinal balancing upon failure of one of the engines.

On airplanes with three engines having a low or medium degree of by-pass, two are located on the side, with the third in the fuselage and equipped with an S-shaped channel. With the appearance of engines having a high degree of by-pass, a grouping with two engines beneath the wing and a third on the tail (Fig. 4.8) possessing some advantages in relation to weight and center of gravity envelope (by comparison with the EoF layout) began to be used. True, the problem of creating ground clearance is made more complex. Location of the third engine in the fuselage allows the length of the tail portion to be decreased and the necessity for nosing over to be eliminated. By comparison with location of the engines above the fuselage, this layout will lead to a weight decrease of 230-450 kg.[5]

15.2. Centering of the airplane. Among the complex problems of tail installation of engines are grouping and centering of the airplane, i.e. finding the mutual locations of the fuselage, wing, engines, and gear, as well as equipment components, passenger seats and baggage compartments. These problems are solved more simply in the planning of light airplanes than heavier ones, which is explained by the increased effect (in the first case) of the /195
relatively large weight of equipment on the centering of the empty airplane, relatively long fuselage length and a decreased distance from the engines to the wing. As the result of a higher commercial return, displacement of centering from the weight of the passengers can be increased, but it can be compensated by advantageous location of baggage compartments.

Problems of grouping and centering are connected with the questions, complex for airplanes of this layout, of stability when

[5] Aviation Week, April 22, 1968, p. 62.

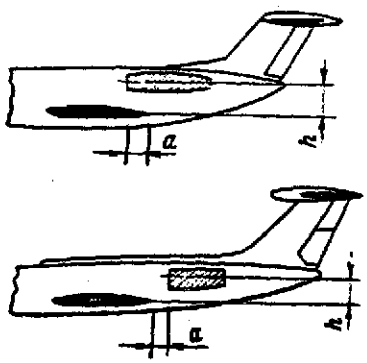

Fig. 4.7. Arrangement of two and four engines.

standing and upon lifting the nose wheel during takeoff. They are solved by means of selecting the optimum value for gear placement from conditions of: stability when standing or moving around the airport (in any variations of loading), the interdependency of gear placement and empennage effectiveness at the moment of rotation during takeoff (with the smallest value for angle of horizontal stabilizer deflection ϕst), and also by means of selecting a proper arrangement for the passenger cabin and baggage compartments. Rationale in arrangement will lead to achievement of the minimum envelope for operational centering and, chiefly, minimum displacement from the commercial payload. It should be noted that solution of the first of these problems depends on the selection of means for providing stability of the airplane on the ground and that it is solved in different ways for different airplanes.

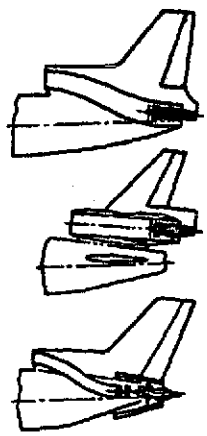

Fig. 4.8. Arrangement of the third engine.

The complexity of these problems is explained by the following: 1) a sharp displacement of the center of gravity of an empty airplane to the rear as a result of moving the power unit to the tail portion of the fuselage; 2) a significantly high effect of the commercial payload on displacement of the airplane's CG (with EbW, the CG under the effect of a load moves to the rear by 4-6%, and with EoF, it moves forward by 20-23% of the mean aerodynamic chord); 3) the increased values for gear parameters e_0 and e_{ef} (see Fig. 4.4). This is connected with the opposite mutual position of the CG of the empty and loaded airplane (see Fig. 4.4, points 1 and 2).

Concerning the band of change of the airplane's centering in flight, the EoF layout does not introduce anything new. During judgment of the EoF layout in the press (which also continues to the present) the question of centering also proved to be disputed. Actually, its solution was made more complex during both planning and modification. The question of centering also requires increased attention during operation (when preparing the airplane for flights). However, assertions of complexity in pilotage or about the presence of limits in centering reserve are hardly founded. All problems in the final analysis can be successfully solved. The possibility for increasing fuselage length during modifications is also complex, but not eliminated.

During the creation period of second generation airplanes, a tendency appeared toward increasing the centering envelope, corresponding to requirements of operations and connected with the striving to reduce the time spent on preparing for flights. This actually led to definite difficulties, but has no relationship to the problems connected with the EoF layout. A wide centering envelope, on the order of 17-20% of the mean aerodynamic chord and greater can also be successfully attained on these airplanes. It should, by the way, be noted that the operation freedom necessary for distributing all types of loads characterizes not so much the envelope of takeoff centering as the envelope corresponding to the zero fuel weight of the airplane. With rational selection of the fuel system, flight centering is practically located in the permissible range if centering of the airplane without fuel is satisfactory. Modern requirements for an even wider envelope will lead to heavier structures as the result of an increase in empennage dimensions and, consequently, the weight of the fuselage and other parts of the airplane, as well as fuel reserve with this. In connection with this, the question of the envelope actually required arises, even more so since automatic systems for determining weight and centering are developed and are being ever more widely used.[6] /196

The basic requirements of grouping which are more complex for airpanes with EoF include:

1. Locating the optimum mutual location of the fuselage, wing, engines and gear. Location of the wing along the fuselage length toward the rear decreases the arm of the empennage. Placement of the engines behind the rear edge of the wing is limited by the conditions of their operation at high pitch angles and determines utilization of the space in the fuselage, since it is connected with the rear limit for locating seats. The position of the gear determines the position of the rear spar of the wing and the latter has an effect on the amount of flap in the part of the wing which is most effective for it. At the same time, the mutual placement of the parts mentioned are also determined by conditions of the center of gravity envelope.

2. Rational placement of equipment with consideration for operational requirements (easy access), and minimum loss in weight and energy by shortening wire harnesses. The major task in calculating centering of an airplane with EoF is the achievement of the forwardmost position of the CG of the empty airplane and the minimum value for gear spread (e_0) with a sufficient reserve for stability of the empty airplane (e_{ef}) on the ground.

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[6] The AWC-I and AWC-II systems (inventors certifications by V. M. Sheynin and A. A. Maslenikov No. 171137 from June 4, 1961 and No. 164449 from October 4, 1962) "Byulleteny izobreteniy," No. 15, 1964, p. 64 and 1965, No. 10, p. 75.

The main gear legs on an airplane with EoF cannot be placed with the parameters used on airplanes with EbW. The gears are installed relative to the envelope for takeoff centering, and the value of the limiting parameters (relative to the CG of the empty airplane) is greater on airplanes with EbW and the reserve of stability on the ground is higher. While on airplanes with EoF, the main gear is installed from conditions of providing stability of the empty airplane on the ground, the gear spread relative to takeoff centering reaches a very high value. This occurs even in cases where grouping is conducted under conditions of achieving empty airplane centering within the limits of 40-45% of the mean aerodynamic chord. The great gear spread will lead in turn to an increase in the horizontal stabilizer.[7] The creation of empty airplane centering within the limits shown will lead to an increase in the nose (destabilizing) part of the fuselage (as a result of more rearward location of the wing) and to an increase in the vertical stabilizer, whose dimensions will increase to an even greater degree with consideration for damping. /197

The minimum gear spread relative to takeoff centering must be obtained by means of grouping from conditions of achieving the possible frontmost centering of the empty airplane. For this, the following are necessary: move the wing toward the tail portion of the fuselage, move the maximum part of the equipment into the nose portion of the fuselage (including such equipment whose location near the power unit is advisable both with respect to weight and reliability); locate the passenger seats at the rearmost limit; create a large baggage compartment in the tail part of the fuselage (beneath the floor). As a result, the weight of the airplane will increase significantly due to the increase in dimensions of the empennage, lengthening of the wiring harness and weighting of the power sources, whose power must be increased due to the increased loss. Arrangement of the gear is complicated. Thus, on a wing with $\chi = 35°$, a rational placement of the gear would not allow it to move outside limits of 42-44% of the mean aerodynamic chord. Further displacement to the rear of the components for fastening them onto the wing will lead to a decrease in flap area. The height of the profile in the rear part of the wing becomes insufficient for locating the legs in the selected position. Locating the passengers close to the engines deteriorates conditions of comfort. The baggage compartment in the tail portion of the fuselage which is too large will prove to be inconvenient, not only for containers but also for normal loads. Therefore, these measures will lead to a number of complications, and obtaining the center of gravity for an empty airplane on the order of 30-35% and thereby providing stability of the airplane on the ground without taking additional measures is not successful.

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[7] This is connected with one of the conditions of selecting S_{ho} (see Chapter 16).

15.3. Development of the layout. The first foreign airplanes with EoF had a number of deficiencies. Primary among these were: heavier structure (see Chapter 14) and forced displacement of many equipment components far away from the engines (from conditions of centering). The latter not only leads to weighting, but reliability decreases and conditions of servicing are deteriorated. When planning the Il-62, a new layout was developed for landing devices,[8] which significantly increased the effectiveness of airplanes with EoF and represents their further development. This schematic differs from known ones in that the main gear legs are not located on one end of the total center of gravity envelope, but inside it (at a very small distance from the envelope of flight centering, but in front of the CG for the empty and fitted airplane) and with the presence of a fourth (tail) support, which is fitted with a three-steering wheel (Fig. 4.9). This support is used when the airplane is standing and during movement of an unloaded airplane around an airport. During takeoff and landing, during taxiing for takeoff and toward the air terminal it is in the retracted position. The support provides reliable stability of the airplane on the ground during any sequence of loading baggage compartments, simplifying operations. To provide controllability of the airplane during taxiing, contact of the nose wheel with the ground is required. With an unloaded airplane (when the CG is aft of the main gear) it is achieved by creating the required pressure in the shock absorber of the tail support, which also presses the nose wheel against the ground. The new schematic allowed: installation of the main gear legs behind the rear spar of the wing with minimum fastening part dimensions; location of this spar in a higher part of the wing (not pushing it backwards); maintaining the vertical position of the legs (in the opposite case it had to stand at an angle). All this had a favorable effect on the weight of the structure. Besides this, this layout allowed limitation of the horizontal stabilizer to significantly small dimensions, at the same time providing good stability of the airplane at all angles of attack right up to those beyond the critical one. The tie between empennage dimensions and gear displacement is evident from the diagram of active forces

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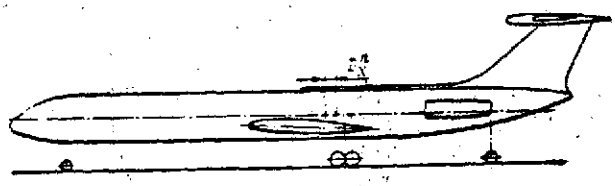

Fig. 4.9. Diagram of landing devices with four supports.

[8] Patented by S. V. Il'yushin, D. V. Leshchiner, V. M. Sheynin and G. Ye. Dolgushev. They received: in the USSR -- inventors certification ("Byulleteny izobreteniy," No. 5, 1972, p. 214) B1114, in England -- patent 1110642, in Belgium -- 155070, in France -- 1497835, in the FRG -- 1289745, in Italy -- P13068, and in India -- 109209/1967.

at the moment the nose wheel is lifted (see Fig. 4.4) and equation (4.1) whose designations are given on the figure.

$$P_{hs} = \frac{(G_0 - Y)e''_0 + M_z^{b/hs} + \Sigma R \cdot a}{L_{hs}} . \qquad (4.1)$$

Another advantage of this layout is the possibility for locating equipment components connected with power sources near the engines. This not only increases reliability and reduces weight, but also improves operational possibilities, since the components are installed above the floor, having good access not only on the ground, but also in flight, which simplifies servicing. On airplanes with EoF, but with the old gear layout, due to centering conditions, components must be located in the nose part of the fuselage (beneath the floor). /199

In total, the new layout for landing devices led to a significant decrease in the weight expenditures connected with the EoF grouping (see Fig. 4.6). In weight characteristics, the Il-62 concedes practically nothing to equal-sized airplanes with EbW grouping (Table 4.1), which supports the effectiveness of the solution examined. It should be noted that the weight result of using this layout on airplanes of different tonnages is not identical, since the weight expenditures with the EoF installation are also different.

TABLE 4.1. WEIGHT EFFECTIVENESS OF AIRPLANES WITH DIFFERENT ENGINE GROUPING

Designation	Airplanes w/ EbW		Airplanes w/ EoF	
	DC-8	Boeing 707	Super VC-10	Il-62
Load ratio in %	58	57.5	53	57
Relative weight of airframe in %	24.4	25.3	—	25.0*

* With consideration for weight of the pods. Without considering their weight, 23.1%.

In this way, one of the main grouping peculiarities of the Il-62 is the new four-support gear layout. It affected: the dimensions and arrangement of the airplane; the weight and economic effectiveness; an increase in reliability in equipment systems and

simplicity of their servicing; simplicity of the loading and unloading process (dropping the strict sequence). It is also necessary to note that the four-support layout is an organic feature of this airplane. A fourth support cannot, for instance, be added to an existing airplane with the same results. The gain would be only operational, but the airplane structure would be heavier. Removal of the fourth support is possible, since the essence of the layout is not in it but in the location of the main gear legs. Stability of the airplane on the ground (with this layout) can also be provided with other means listed below.

The four-support gear layout is evidently the best, but not the sole solution. Other methods for decreasing displacement of the wheels from the takeoff position of the CG (e_0) and providing stability of the airplane on the ground are, naturally, possible. Displacement of the relative CG of the empty airplane (e_{ef}), providing sufficient freedom during loading and unloading of the airplane lies within limits of 8-10% of the mean aerodynamic chord. If e_{ef} = 4-5% of the mean aerodynamic chord is used (due to a decrease in e_0), then an additional support of, for instance, the type of a built-in gangway with a reinforced structure, is necessary. Another method consists of locks on the axis of rotation of the leg relative to the wheel carriage. A third consists of development of a main gear design with a movable leg. The first of these will not lead to a decrease in weight, but will more likely increase it, and does not provide for free movement of an unloaded airplane around an airport. The two others sharply decrease takeoff safety and have therefore not been used. Installation of gear legs at an angle of up to 5-6° has been approached, and somewhat eases the position, but it does not totally solve the problem. /200

The materials of this section and the results of a weight analysis (see Chapter 14) lead to the conclusion that: in case the layout with EoF is used, it is necessary to seek principally new solutions for a number of planning problems allowing the creation of structures with weight effectiveness approximately corresponding to airplanes with EbW.

15.4. Geometric parameters of airplanes with EoF. The geometric parameters of wings on airplanes with EbW and EoF placement are practically the same. Some divergences are observed only in the dimensions of the mechanization means and extension along the rear edge. Concerning structure, a "clean" wing is distinguished by its more strict force diagram and somewhat wider torsion box in the center section part. The latter, like the increase in extension dimensions, is connected with a significant increase in main gear leg shift (displacement to the rear).

The EoF configuration often leads to some increase in length of the fuselage and its lengthened λ_f. Is it possible to see this as a decrease in the degree of space utilization and, consequently,

as weight and economic losses? With a typical schematic for landing devices (when it is necessary to locate the maximum equipment in the nose part of the fuselage due to centering conditions), apparently, yes. With the four-support gear layout, these losses are successfully avoided. In this case, all equipment is installed in the engine section, and the freed space in the subfloor nose part is used for increasing baggage compartments. With EoF installation, the relationship between the nose and tail portions of the fuselage (located in front of and behind the airplane's CG) is changed. The nose part increases from 50-52% (in airplanes with EbW) to 57-58% of the length of the fuselage.[9]

The pods of two- and four-engine airplanes are distinguished by the most innovation. The new configuration, besides this, regenerated, as was noted, the three-engine layout, which has its own differences. The value of geometric parameters of these pods are changed in insignificant limits. For instance, in the small Lockheed "Jet Star" airplane and the heavy Super VC-10, pod lengthening λ_p is equal to 3.42 and 3.47 respectively and in the "Caravelle" airplane, it is 3.48.[10] Peculiarities in the landing gear of airplanes with EoF are examined above. /201

In the development of passenger aviation, a tendency is observed toward increasing the relative dimensions of the empennage and making its layout more complex. The total relative area of the empennage in jet passenger airplanes of the first generation with swept wings comprised an average of 34% of the wing area, in the second generation it comprised up to 43%, and in the third generation airplanes it reached 53%. Its relative weight resulting from the increase in dimensions and complexity of the layout increased by 50-100%. Thedimensions of the empennage affect not only the weight of its construction but also the weight of the fuselage and with consideration for the coefficient of increase, the weight of other parts of the airplane.

The area of the horizontal stabilizer (ho) is determined by conditions of stability and controllability at low flight speeds (at all angles of attack up to beyond the critical ones); the amount of the moment necessary for lifting the nose wheel during takeoff; conditions of cruise flight with a set center of gravity envelope. The degree of wing mechanization also has an effect. While some conditions are limiting for some airplanes, others are for others. With this, weight is one of the factors which determines advantages of various empennage layouts, other conditions being equal. The area of the horizontal stabilizer, like the total area in airplanes with EoF, increased, regardless of the fact that

[9] These values are also connected with the angle of wing sweep [62].

[10] These values are given for pods of engines with low and medium degrees of by-pass.

the large aerodynamic surface of the pod creates an additional stabilizing moment which partially unloads the horizontal stabilizer. The reason is the decreased L_{hs} as a result of the backward shift in the CG of the airplane and the increase in gear displacement (from the takeoff position of the CG). To increase L_{hs}, to remove the horizontal stabilizer from the cone of the exhaust gas stream and the zone of intensive engine noise, and to reverse thrust, the T-shaped layout, using a swept vertical stabilizer, began to be used. As a result, the static moments (A_{hs}), expressed in the function of the relative amount of the conditional fuselage volume [70] were successfully maintained in some limits (Fig. 4.10). A feature of second generation airplanes which effected the value of horizontal stabilizer area was the increase in operational requirements for the center of gravity envelope, whose limits were increased from 12-14 to 17-20% of the mean aerodynamic chord and more.

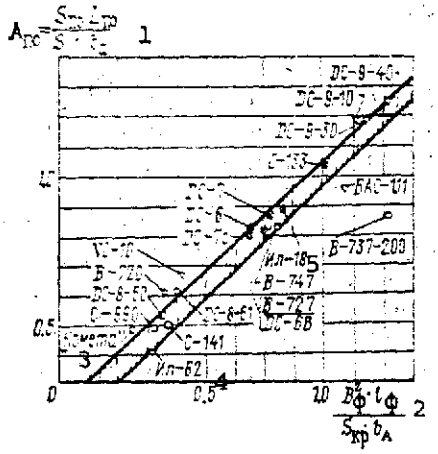

Fig. 4.10. Parameters of effectiveness of the horizontal stabilizer of low-placed (o), T-shaped (▽) and propeller airplanes (⊗) according to data of work [70].

Key: 1. $A_{hs} = (S_{hs}L_{hs})/(S \cdot b_a)$; 2. $(B_f \cdot l_f)/(S_{cr} \cdot b_A)$; 3. "Comet;" 4. Il-62; 5. Il-18

The area of the vertical stabilizer (vs) increased approximately to the same degree as the result of a significant increase in the destabilizing moment due to a large, in this case, area acting like a sail in the nose part of the fuselage. There are also, however, positively acting factors here. The sail area of the pods located in front of the airplane's CG with the EbW configuration, for instance, disappeared; yawing moment declined (upon failure of one of the engines); and the "washer effect" appeared with the T-shaped layout. As a result, the static moments B_{vs} lie in a common band (Fig. 4.11). /202

In this manner, the T-shaped layout of the empennage became practically the only one possible with the EoF configuration. However, the advantages and disadvantages of this layout became clear only with other conditions being equal, i.e. with the EbW configuration, in which both empennage designs are possible. The Lockheed firm realized the T-shaped layout on two military transport airplanes with EbW location. It is not used on passenger airplanes with EbW.

The T-shaped empennage design has still another peculiarity. With this design, a stall can develop up to very high angles of attack (delayed stall), which occurs as the result of the highly

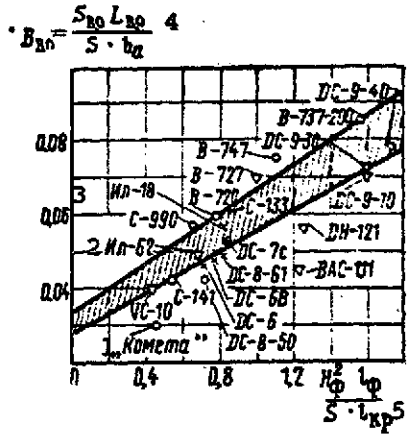

Fig. 4.11. Parametric effectiveness of the vertical stabilizer.

Key: 1. "Comet;" 2. Il-62; 3. Il-18; 4. $B_{VS} = (S_{VS}L_{VS})/S\cdot b_a$; 5. $(H_f^2 l_f)/S\cdot l_{cr}$

placed horizontal stabilizer falling into the disturbed airstream from the wing at an angle of attack exceeding the critical one. Being very wide and having a low dynamic pressure in the center, this stream deteriorates effectiveness of the horizontal stabilizer as a means of providing pitch stability. As a result, with a higher than critical angle of attack, the static stability of the airplane will be lost to a significant degree, which can lead to a still greater increase in the angle of attack. This peculiarity in the design led to the necessity for installing control column sensors on a number of airplanes preventing the airplane from approaching angles of attack close to the critical one. Other solutions were found for other airplanes.

As was shown, the T-shaped and low-placed empennage designs have various advantages and disadvantages with respect to weight. The gain in weight of the first of these designs becomes more apparent with the increase in dimensions of the airplane and depends on the length of the fuselage. For instance, in a military transport airplane with a lower (by comparison with equal-tonnage passenger airplanes) fuselage length, the relative amount of horizontal stabilizer movement (with its location on the vertical stabilizer) turns out to be somewhat greater. This also leads to a relatively large decrease in the area of the horizontal stabilizer. The relative amount of the decrease in area and weight depends also on the sweep of the wing. /203

Chapter 16. Peculiarities of Tail Mounting of Engines on Airbuses

In the planning of wide-fuselage airplanes (airbuses) with a qualitative increase in its flying characteristics (flight speed) and geometric parameters (length and diameter of the fuselage) qualitatively new phenomena have been observed, leading in particular to the reevaluation of the advantages and disadvantages of tail mounting of engines. Used on wide-fuselage airplanes, this layout lost many of the advantages which it possessed earlier on second generation airplanes. The character of its deficiencies in a quantitative and a qualitative relationship also changed simultaneously.

Thus, with an increase in the M number from 0.85 to 0.9, aerodynamic noise becomes dominating. Therefore, placement of the engines on the fuselage does not provide any sort of advantages

with respect to decreasing the level of noise in the cabin and improving comfort. Besides this, with M greater than 0.85 on a wide fuselage, the possibility of shaking from engines installed on the tail appears. On airbuses, as a result of the same reasons, it is not as a rule, possible to realize the advantage of a "clean" wing, namely through mechanization along its entire span, which is possible with the EoF configuration. The fact of the matter is that the effectiveness of the outer aileron at a high M number is insufficient. This leads to the necessity for installing an additional (inner or "speed") aileron. With the EbW configuration, the latter is located in the zone of the engines since small angles of its deflection do not hinder this. Consequently, in the presence of a "speed" aileron, the dimensions of the flap with the two types of engine configuration (EbW and EoF) are approximately the same.

At the same time, it is difficult not to agree with the fact that on an aerodynamically "clean" wing, it is simpler to obtain a higher value for takeoff coefficient cy. Still further, the mutual position of the wing and fuselage, more to the rear with EoF, simplifies the problem of achieving the maximum value for aerodynamic quality.

One of the advantages of the EoF configuration is, as was noted, removal of the engines from the ground, which eliminates their sucking in dirt and stones. Intake of dirt from beneath the main gear wheels is prevented by the flaps, which are extended at that time. With a significantly greater fuselage length in airbuses (by about 10 m in the L-1011 by comparison with the DC-10) the flaps do not serve as a protective means. /204

Problems of configuration and centering are also complicated, and they are not simple with the EoF location anyway. This is connected with a sharp increase in the relative weight of the commercial payload (from 15 to 25% with comparable tonnage of the airplane) and with an increase in its effect on centering shift. With EbW, the center of the cabin is located at 45-50% of the mean aerodynamic chord, and with EoF, it is displaced forward to 22-27% of the mean aerodynamic chord. While an airplane with EbW and this kind of commercial payload must have a centering envelope no less than 20% of the mean aerodynamic chord, with EoF it is still greater, which is connected with definite weight losses.

Qualitatively new phenomena, connected with the quantum jump in many parameters of airbuses, also appeared in the quantitative evaluation of schematic weight expenditures. Their value is illustrated in Fig. 4.6, in which line I is true for airplanes of the second generation with two, three and four engines, and a weight of up to 60, 100 and 160 t respectively. The line for airbuses (Ia) is true only for the four-engine configuration. Mixed arrangement of three engines (two on the wing, one on the fuselage) in a weight relationship turned out to be equal to tail

arrangement of all three engines. The two-engine layout also turned out to be approximately equal. While location of any number of engines on the tail of second generation airplanes was always connected with weight expenditures, for wide-fuselage airplanes with large diameter engines, this is true in only one of three cases, and their relative values decreased significantly.

This is the result of three reasons.

1. For the purpose of creating the required clearance from the ground, large diameter engines are located far in front of the wing in an attempt to decrease the height of the gear and improve aerodynamics of the airplane. This makes the pylons heavier to a larger degree than the increase in their height, and the weight becomes commensurate with the weight of the pods. (The latter are weighted as the result of the necessity for sound dampening liners to decrease noise in areas. This relates to an equal degree to airplanes with EbW and EoF.) The height and weight of the gear legs, regardless of this kind of pylon, are increased (see Fig. 4.5).

2. The favorable effect of locating the engines beneath the wing on the value of the flexion moment and, consequently, the decrease in weight of the wing is reduced with an increase in the degree of by-pass resulting from a decrease in specific engine weight by approximately 20-25%. The increase in thrust in each of these engines up to a large value will lead to a decrease in their /205
number and the moment from unloading also decreases. The increase in weight of the wing (with EoF) decreases due to the impossibility of creating a flap along its entire span.

3. Weighting of the fuselage (from the EoF location) with its large diameter (5.5-6 m) is decreased, since the character of loading of its structure in the calculated case changes. The relative amount of the flexion moment from the engines is significantly less since the inherent weight of the fuselage and the weight of the commercial payload increased by 60 -70% in comparison with an equal-tonnage airplane having a fuselage diameter less than 4 m.

4. With high thrust from each of the engines and with modern airbus dimensions, the number of engines is decreased to three and two. The weight of elements for fastening this number of engines on the tail is significantly lighter than for four. Consequently, tail grouping of engines on wide-fuselage airplane will lead to decreased weight expenditures (see Fig. 4.6). The possibility is not excluded that in the future it will even lead to the opposite result, i.e. to lightening. When the degree of engine by-pass is increased up to 10 and greater, it is possible that various arrangement and operational requirements will also be satisfied in a better way with tail location of the engines. For the time being, however, much speaks unfavorably about this arrangement. Thus, weight expenditures are lower, but with a reduced load ratio they

prove to be significant, also without consideration for the coefficient of increase. The fact of the matter is that the values ΔG_{sc} presented in Fig. 4.6 were found under these very conditions, i.e. under conditions of G_0 = const and $\Delta G_{sc} = \Delta - G_f$ for airplanes with EoF and EbW. While retention of flight range, commercial payload weight, flying, takeoff and landing characteristics are taken as conditions, the weight of the structure and the takeof weight (and consequently, wing area and empennage area connected with it) increase in accordance with the coefficient of increase.

This is true for wide-fuselage airplanes with four engines. About two- and three-engine airplanes, it is possible to state the following:

-- Tail installation of engines also in their application to airbuses remains disputed, and as before it has allies and enemies among designers and researchers;

-- With comparative (in cost) equality in price of the two layouts, the selection of one of them became a question of the designers' taste, or, more precisely, their workmanship aimed for the maximum advantages with one layout or the other (naturally, the specifics of actual conditions also have an effect);

-- In plans for wide-fuselage airplanes (and airbuses in particular) tail installation has had only limited usage.

PART 5. PROBLEMS OF OPTIMAL DESIGNING /206

Chapter 17. Modern Designing Methods

17.1. Development of methods. Designing, as a technical discipline, is a methodological engineering creation and studies methods for single-minded utilization of knowledge for practical purposes. For instance, the contents of the science of aviation planning is made up of: methods of evaluating airplane effectiveness; methods of finding airplane parameters; methods of their optimization; methods of developing tactical and technical tasks for designing; weight calculation theory; grouping and connection theory; and construction theory.

The science of designing is exclusively specific. While a majority of other sciences is occupied primarily with analysis of facts, each of them examining facts in the same way, the contents of designing is a synthesis based on the results of different sciences. The tasks of sythesis are more complex in principle than the tasks of analysis. This is the reason for the special complexity of designing theory and the definite lag of this theory behind practice. While it was possible to reconcile oneself with this lag to some degree during early stages of the equipment's development, it has now become intolerable. This is exactly why intensive investigations have been universally developed recently, directed at development of theoretic bases for designing, the combined concept -- the theory of optimum design. This section of the book is dedicated to the basic problems of this theory in airplane building.

Strictly speaking, the major task of designing, using contemporary terminology, can be defined as the task of adopting a solution. A new science -- operations research [6, 16] is occupied with a qualitatitive analysis of these tasks. From a mathematical point of view, it belongs to a class of variation problems, consisting of solution of a system of equations with many unknowns, under the additional conditions that some functions of these unknowns, called functions of effectiveness or quality (otherwise -- purpose or criterial), assume an extreme value. However, direct /207
solution of these tasks under conditions of actual design is exclusively complex: the number of unknowns (parameters of the design object sought) is very great; the connections between these variables are complex and are often subjected to formalization with great difficulty; formation of the concept of airplane effectiveness and development of corresponding purpose functions proves to be highly complex; expression of the purpose function through unknown problems and finding its extreme represents particular mathematical difficulties. It is therefore absolutely natural that methods for actual designing were at first developed in the direction of finding approximate, oblique means and only at the present time have the more precise direct methods begun to be accumulated. A possible classification for designing methods if presented in Table 5.1.

TABLE 5.1. CLASSIFICATION OF DESIGNING METHODS

Principle of sequential approximations				
Oblique methods			Direct methods	
Copying	Statistical	Analyatical	Optimal	Automatics

17.2. The method (or principle) of sequential approximations characterizes a general approach to the solution of planning problems. In this sense, any method of planning is a method of sequential approximations. Its essence consists of the fact that a set of planning problems is solved gradually with sequentially refined and developed approximations (steps, iterations). Complex problems, using insufficiently precise initial information, can be successfully solved comparatively accurately by this method. The idea of the method is identical to the method known in mathematics with the same name [8].

With different designing methods, the principle of sequential approximations has been developed to a different degree. It has the least meaning in the methods of copying and statistics, since projects fulfilled with these means can be generally seen as the first crude approximations to the optimum result. It has been most developed in the analytical method. Direct methods have definite grounds for refusal to make use of this principle. One of the characteristics phenomena of the principle of sequential approximations during design is division of the design process into stages (development of tactical and technical problems, preliminary studies, sketch, technical and working probjects).

17.3. The method of copying (imitation) consists of imitation /208 of finished constructions, which are used as models (prototypes). Earlier, "constructions" of birds and insects were used as these models, and later, constructions of successful airplanes were used. The use of special airplane constructions for creation of passenger ones should also be included as a phenomenon of this method.

Optimization of the project with this method is not assured, since conditions of optimization, as demonstrated now, change essentially with a change in operating conditions and scale dimensions of the structure. For consideration of this situation, it is necessary that rather complex rules of similarity be adhere to, which, however, eliminates the possibility of using this method in its initial form. At the present time the copying method is rarely used. Its positive role cannot, however, be underestimated. Thus, for instance, study of the "force diagram" of leaves allowed the optimum force diagrams for short wings to be found. Study of the

peculiarities of dolphins swimming allowed a new effective method for laminarization of streamlining to be discovered [36].

Living nature also served as a prototype for modern aviation honeycomb constructions. A multitude of such examples could be presented. The development of bionics, occupied with the study of laws of imitation in living nature, uncovers definite promise for regeneration of this method, albeit on a new basis.

17.4. The statistical method of designing consists of the fact that the parameters of a new airplane are selected using a dependency which came to light as the result of airplane building experience. In essence, this method is also one of imitating prototypes. However, unlike the one mentioned, not one prototype but several are used in it each time. This allows discovery of regularity between the parameters of an airplane and attainment of a more perfect project solution than with simple copying. The appearance of the statistical method was connected with the introduction into design practice of the first, albeit primitive, criteria of effectiveness for an airplane such as, for instance, Everling coefficients [34]. Now, the statistical method in its initial form has also departed into the past. However, its basic ideas were successfully developed later on the basis of modern probability theory and mathematical statistics. The use of statistics remains up to the present time the single means for solving specific planning tasks of the first approximation. We also note that all so-called analytical formulas used during design always contain numerical statistical coefficients and are therefore in essence complex multiple correlation formulas. Finally, without scientific statistics, the forecasting of technical development, /209 so necessary for modern designing, is impossible.

17.5. The analytical method for selecting the basic parameters of an airplane rests on formulas developed on the basis of analysis of functional ties between the parameters of an airplane. Regardless of the approximation of many of these formulas, this method is the most widely used and is without a doubt a step forward in the development of design theory. The solution of many interesting problems, such as: the selection of the airplane's parameters providing maximum range, speed or flight altitude; discovery of the optimum (from the point of view of flying data and weight) values for some parameters of airplane components, for instance, length, thickness or specific loading on the wing, are tied to its development. In the meantime, analytical methods do not encompass all stages of design and are most widely used only during outline determination of the basic parameters of the airplane.

The value of the analytical method as a basis for development of the even more perfected optimization and automatic methods is singularly great. The peculiarities of the first of these are: and increase in the volume of analytical dependencies used and a further increase in their precision; development and usage of

scientific criteria of airplane effectiveness; and widespread usage of high-speed electronic computer equipment during designing. The method of automatic designing consists of automation with a computer system of separate stages or even of the entire designing process as a whole, using, of course, the most highly perfected optimization procedures [13]. At the present time, similar automatic systems have already been created and used, and particularly in airplane building. However, as a whole, the development of this method is a task of the future.

Chapter 18. Criteria of Effectiveness

18.1. Types of effectiveness. As was already noted, the theory of effectiveness is the most important element in design theory, on whose development the development of the project methods themselves largely depends, since selection of effectivness criteria determines the practical value of design results. The question of the number of criteria simultaneously used during designing deserves a great deal of attention. During the time aviation has existed, methods of evaluating effectiveness have undergone great changes. Qualitative methods came into replace the first speculative ones, and in place of partial criteria, applicable for solution of only a narrow circle of tasks, general criteria /210 were developed. As is well-known effectiveness is evaluated by means of comparing the useful effect with expenditures brought about by it. Depending on the actual content and accuracy in determining these two categories, general (i.e. most objective, universal) and partial criteria of effectiveness can be differentiated, without talking about their correctness in essence.

Fig. 5.1. gives a possible classification for the basic indices of effectiveness, worked out in the practice of airplane building. Transport, production and operational effectiveness form a group of partial types of effectiveness of the first level, which have a limited area of usage. These forms of effectiveness in conjunction appear in the group of more complex forms of the second level. And finally, the most objective form of effectiveness of a passenger airplane is the economic one.

Transport effectiveness reflects only that side of an airplane's perfection which depends on its technical indices, such as load ratio, aerodynamic quality and specific fuel consumption. Both these indices and products from them are used for its evaluation. The advantage of the examined criteria is their simplicity and descriptiveness. A detailed analysis of criteria of transport effectiveness is presented in work [62]. The criteria presented there are based on a comparison of available productivity with expenditures of the mass of the airplane (G_{ef}) and fuel energy $t = \frac{G_{cp}LV_r}{G_{ef}G_f}$ (where V_r is the route (average) flight speed). The

idea of a similar approach in the future was developed in work [2], where the effect of speed on the increase in structural weight and on fuel consumption is shown in detail.

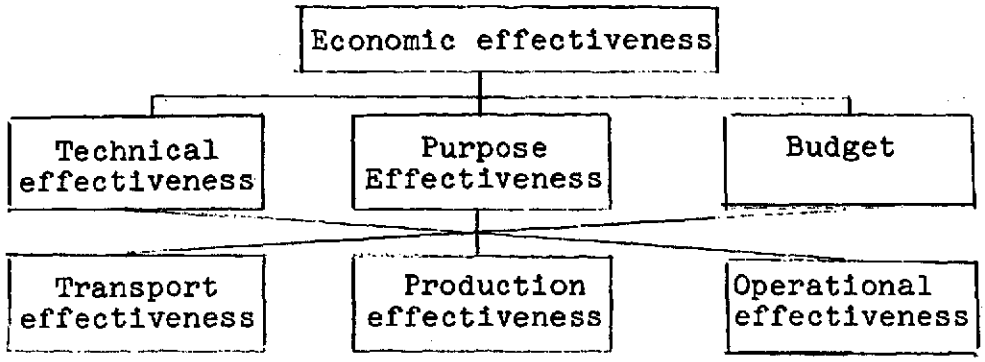

Fig. 5.1. Relationship of Types and Criteria of airplane effectiveness.

The production effectiveness of an airplane reflects its perfection as an object of industrial production. It depends on properties of the structure such as level of technology, interchangeability, level of normalization and so forth. In the meantime, corresponding criteria are insufficiently developed. All other conditions being equal, this form of an airplane's effectiveness can be judge according to the cost of its production. /211

The operational effectiveness of an airplane reflects its perfection as an object of technical operation. It depends on such indicators as the airplane's longevity, reliability, operational technical level and so forth. Sufficiently convenient criteria for evaluation of this type of an airplane's effectiveness have not yet been found. All other conditions being equal, this form of effectiveness can be judge according to a group of indicators such as the labor consumption and cost of technical servicing of the airplane, the probable flight hours per year, the security of its construction and others.

The technical effectiveness of an airplane is its generalized characteristic and in essence it is evaluated with such well-known indices as cost per ton-kilometer (t km). Calculation of the value of this index is accomplished according to known methods [3, 18], whose essence can be expressed with the formula

$$a' = \frac{K_i}{G_{cp}{}^{\eta} K_{tl}} \left\langle \alpha \frac{G_e}{V_r} + \beta \frac{G_f}{L} \right\rangle , \qquad (5.1)$$

where α -- specific measure of the airplane's cost with consideration

for repairs and technical servicing; β -- cost of a unit weight of fuel; K_i -- coefficient of indirect costs; K_{tl} -- coefficient of loading of the airplane.

Using economic categories, a proper comparison of all indices of not only transport (through components G_{cp}, G_f, G_e, L) but also productive and operational effectiveness of the airplane (through coefficient α) are taken into account in the index of cost per ton kilometer. This is precisely why the cost per ton kilometer can be seen as an index of its technical effectiveness. The value of this index cannot be underestimated, although it is necessary to emphasize that it can be used for solution of only part of the problems of optimization.

Purpose effectiveness of the airplane is the same sort of complex concept as technical effectiveness, and evalues the same indicators but in a different aspect. This type of effectiveness reflects the degree to which the airplane satisfies those requirements for which is was created, i.e. such of its properties as speed, range, load capacity, degree of comfort and so forth. This type of effectiveness is reflected in the amount of the scientifically based rates for shipments. We note that development of these rates is extremely complex and is not yet finalized.

Investment capacity is a third complex index of an airplane's /212
effectiveness. It is measured with the cost of the airplane and the other means in conjunction with it which are necessary for accomplishment of a set volume of shipments during a determined time with other conditions being equal.

18.2. Economic effectiveness. The essence of economic evaluation of the effectiveness of a machine, as is known, boils down to comparison of the total expenditures in labor on its creation with subsequent savings in the ongoing expenses of labor from its utilization. (We note that the cost is only a measurement of labor expenditures.) The conditions of economic effectiveness with this consist of the fact that labor expenses on creation of the machine were less than labor savings in the process of its operation. With this, since all labor processes continue through time, additional conditions arise that the machine provides a definite labor productivity, or in other words a definite rate of "self support." It is perfectly apparent that from a national economic point of view, such an evaluation of effectiveness of a machine is the most important. The requirement listed above corresponds to the criterion of profit norm or the coefficient of profitability, whose strict basis is given in the theory of optimally planned economics [30]:

$$\frac{S - C}{K_s} \geq E_n. \qquad (5.2)$$

Here, S is the price of finished production, i.e. the total required labor expenditures on its creation; C is the net cost of the same production, i.e. the corresponding individual labor expenditures; K_s is the price of a machine, i.e. the total required labor expenditures on its creation. (K_s also includes all expenses connected with the introduction of the machine into operation, including the required return means); E_n is the normative of expenditure effectiveness or the normative of profitability. Under conditions of optimal economics no difference will exist between both indices. Under conditions of actual economics, the difference exists, however it does not effect the form of the criterion. In practice, $E_n = 0.12$ is used.

In an expanded form applicable to an airplane, Eq. (5.2) takes on the following appearnce:

$$\frac{(s - c)A}{K_c} = \frac{(s - c)G_{cp}V_pW_n}{K_c} \geq E_n, \qquad (5.3)$$

where s is the fare per ton-kilometer; c is the cost per ton-kilometer; A is the annual productivity of the airplane; t-km/year; /213
K_c is the cost of the airplane (including return and other basic funds immediately connected with its operation); W is the annual hours of flight of one airplane.

Unfortunately, at the present time while prices still do not accurately reflect the total required labor expenditures, use of criterion (5.2) is connected with known difficulties. Therefore, one of the most important problems for modern aviation economics science, which in truth depends on solving the problem of price within the framework of the entire national economy, is the problem of perfecting fares. The first step in this direction might have been consideration of the economic value of speed in the amount of aviation fares. The idea of a corresponding evaluation was already expressed in 1936 by N. N. Fadeyev, and was later used by Ye. A. Ovrutskiy for development of a criterion which was named the coefficient of "economy of speed" [3, 40].

$$K_V = \frac{\sqrt{V_r}}{c}.$$

At the present time, however, it is expedient to use this idea not for conclusion of new criteria, but to reflect speed in the amount of the fare. This problem can be solved in the following manner. If we assume that some fare s is real for speed V', then the savings in time Δt per unit of the course because of the greater speed V will be equal to

$$\Delta t = \frac{1}{V'_r} - \frac{1}{V_r},$$

where V'_r and V_r are the route speeds corresponding to speeds V' and V. The admissible change in the fare Δs due to this savings in time will be

$$\Delta s = N\Delta t, \qquad (5.4)$$

where N is the monetary equivalent of the time spent enroute during the course of an hour of a passenger of ton of cargo.

From the above, it is apparent that for a basic improvement in the cost system, polliatives are unavoidable. This polliative is a known criterion for the minimum adjusted expenditures, and was officially introduced into calculation practice in 1960. If we view the interchangeable variations, which are identical according to quantity and quality of production output (these can be variations of an airplane project with a given tactical-technical problem in the process of its development), we can assume

$$S = \text{const} \qquad (5.5)$$

and, consequently, eliminate product cost from the examination. /214
The equal cost of these variations will then be expressed by the condition of equality in adjusted expenses $C_i + E_n K_{si} = \text{const}$, and the variation in which the "adjusted expenses" prove to be minimal will be the optimum, i.e. the criterion of effectiveness will have the appearance

$$C_i + E_n K_{si} \to \min \qquad (5.6)$$

(Apparently, both here and in the future, instead of C and K_s, it is possible to use specific indices: cost per unit of production; in particular, the cost per ton kilometer and capital expenditures on the same unit.)

The following criterion in aviation practice is also interesting: $G_0 \to \min$. This should be understood to mean that with an optimum variation of an airplane project, all other conditions being equal, takeoff weight must be minimal. The use of this criterion, however, can be justified only in a case where the decreases in the airplane's weight will not be in conjunction with the usage of means which essentially affect its cost.

If in addition to condition (5.5), we also assume

$$K_{si} = \text{const}, \qquad (5.7)$$

the criterion of effectiveness becomes the cost of annual production volume or from force of the condition of quantitative sameness of variations stipulated above -- the cost of the unit of production and particularly the cost per ton-km, i.e. $c_i \to \min$.

In this manner, this index can be examined as a criterion of economic effectiveness only with liminations (5.5) and (5.7) indicated.

Concluding this section, we turn out attention to the fact that none of the economic criteria formula presented above are entirely accurate, inasmuch as the economic role of time is not fully considered in them. It can be stated that differently timed economic phenomena can be compared only by being brought to a single moment in time [30]. Thus, for instance, if expenditures K_s are produced earlier than the moment in time examined by τ years, at that moment in time that it must be considered as $K_{s\tau} = K_s(1 + E_n')^{\tau}$. At the present time, $E_n = 0.08$ is used.

Consideration of the time factor is especially necessary in evaluating the effectiveness of aviation equipment, for which rapid rates of obsolescence are characteristic and, in particular, when comparing variations of airplanes with different period for planning, construction and introduction into operation. Consideration of the time factor allows in particular a new approach to the problem of feasibility for planning civilian airplanes on the basis of airplanes for a different purpose. It has been proven that an original passenger airplane has all the bases for being effectively planned by this method. However, in some particular cases, the planning /215
method mentioned leads to a savings in time which under set actual conditions has a special significance. Thus, for instance, timely creation of the Tu-104 passenger airplane on the basis of the Tu-16 accelerated the appearance of civilian jet aviation into operation. The overall positive effect of this is in no way expressed through the valuation of economy of only the Tu-104 itself (one of the most important aspects of the effect of the time factor is also the possibility for including it in the economic calculations examined in Section 4.5).

Chapter 19. Method of Optimal Planning

19.1. The purpose of optimal planning. The difference between the method of optimal planning and all those review above consists of the fact that it is a direct method and, consequently, can provide determination of the parameters of the planned airplane,

which is really the best example corresponding to the technical problem. There is basis in the statement that this method allows an increase in the airplane's effectiveness by 10-20%. The mathematical model of the planning process, already mentioned above (17.1) here becomes the immediate object of study and can be written in the form of the following system of equations:

$$\left.\begin{aligned}
&F=F(\alpha_1\alpha_2\ldots\alpha_n;\ x_1x_2\ldots x_n)\to\max(\min),\\
&Y_1=Y_1(\alpha_1\alpha_2\ldots\alpha_n;\ x_1x_2\ldots x_n)=0,\\
&Y_2=Y_2(\alpha_1\alpha_2\ldots\alpha_n;\ x_1x_2\ldots x_n)=0,\\
&\ldots\ldots\ldots\ldots\ldots\ldots\ldots\\
&Y_n=Y_n(\alpha_1\alpha_2\ldots\alpha_n;\ x_1x_2\ldots x_n)=0,\\
&U_1=U_1(\alpha_1\alpha_2\ldots\alpha_n;\ x_1x_2\ldots x_n)\geqslant 0,\\
&U_2=U_2(\alpha_1\alpha_2\ldots\alpha_n;\ x_1x_2\ldots x_n)\geqslant 0,\\
&\ldots\ldots\ldots\ldots\ldots\ldots\ldots\\
&U_n=U_n(\alpha_1\alpha_2\ldots\alpha_n;\ x_1x_2\ldots x_n)\geqslant 0.
\end{aligned}\right\}\qquad(5.8)$$

Here F is the purpose function; $\alpha_1\alpha_2\ldots$ are the set parameter of the airplane; $x_1x_2\ldots$ are the sought parameters of the airplane; $Y_1Y_2\ldots$ are the functions of interconnection of the parameters (functions of limination, i.e. weight, aerodynamic, economic and other dependencies); $U_1U_2\ldots$ are the functions of the total limitations of the problem (functions of area liminations).

The problem examined (5.8) is a problem at the extreme with liminations. As it it known, its peculiarity is the fact that the /216 number of extremal solutions will be greater than one; among them will be an unconditional extreme, lying inside the area defined by limitation equations, and several extremal points on the edge of this area. Modern level of development of planning theory, mathematics and computer equipment still does not allow optimal planning problems to be solved in all their conceivable fullness, as was already spoken about previously. Therefore, for the time being, separate partial problems, limited both in the scope of parameters considered and in their character are being studied. In connection with this, it is possible to talk about separate directions in this theory, such as optimization of planned (output) flight parameters, paths and levels; optimization of working parameters and structural force diagrams of the airplane based on the theory of "minimum structural weight;" optimization of partial planning and construction solutions and organization of the planning process based on line control and planning methods.

Output parameters of an airplane should be understood to mean those parameters comprising the content of the tactical-technical problem and representing, therefore, immediate interest for the orderer, i.e. speed, range, commercial payload weight, takeoff

weight -- sometimes, takeoff and landing data and so forth. Working parameters must include the more numerous and more detailed characteristics of the airplane defined on the basis of output parameters, i.e. geometric parameters of the wing, fuselage and empennage, technical characteristics of the systems and so forth. The relationship of the airplane's parameters to one category or another is arbitrary and depends on formulation of the tactical and technical problem. Optimization of the structural load diagram of the airplane indicates study of the optimum distribution of the structural material under some set conditions and limitations. Optimization of partial project solutions should be understood to mean the valuation of separate solutions during planning, such as, for instance expediency of decreasing empty airplane weight through usage of new, more expensive materials (equipment), expediency of increase in aerodynamic qualities of the airplane at the expense of increasing its weight and so forth. Optimization of an airplane in any of these directions is realized with the presupposition that in other directions, parameters and characteristics of the airplane are already known. For instance, optimization of working parameters presupposes a determined set level of the airplane's weight perfection, which is reflected in the coefficients of weight formulas. In this manner, optimal solutions in each direction are conditional. Nevertheless, this optimization, reflecting all the same principles as sequential approximations, also has a great significance, in particular because optimums in equipment are usually highly slanted and the approximation to it is sufficiently effective. As was shown above, a definite relationship to the problem of optimization of an /217
airplane also has a system of line planning and control for planning operations. As is known, this system allows optimization according to time periods and cost of the entire process of creation of the airplane, i.e. it affects all its parameters indirectly (with consideration for obsolescence of equipment) and, consequently, also affects other directions of optimization.

In conclusion, attention should be paid to the fact that actual planning solutions cannot be studied, except for theoretical ones, and also to many other considerations (for instance, the presence of various materials, engines, apparati, the level of production development and so forth). In other words, practical solutions do not necessarily have to accurately coincide with theoretic ones.

19.2. Optimization of planned parameters. The basis for selection of planned parameters of an airplane is transport and other more general requirements of that economic region (or government as a whole), that the airplane is intended to serve. The meaning of a literate definition of planned parameters, i.e. formulation of the tactical-technical problem, is not subjected to doubt and is not in need of clarifications. In particular, it is important that the tactical and technical problems do not limit the possibilities for further stages of optimization of the airplane. However, up to recent times, the required attention has not been paid to this problem in machine building in general. Only recently

has progress in the solution of this problem been noted, and it was connected with the development of a new direction which received the name "economic planning of machines" [37].

The optimization of planned parameters of airplanes, like other transport means, requires consideration of not only engineering and economic phenomena for its solution, but also of social ones. The mathematical model of this problem is especially complex. It is distinguished by the fact that besides the determined parameters in it, undefined ones may also be present. In overall formulation, these problems prove to be very complex. Therefore, for the time being, only their separate partial variations are being examined, for instance the following components: for a given economic region with a combined transport network, selection of the most effective of a number of several planned variations; determination of optimum direct flight range for a given route and at a set speed, and; determination of the optimum calculated range of the airplane if it is known that it will be utilized within some range spread.

The first of these problems was examined by, for instance, Huber[1]. To simplify solution, the mass of profit belonging to one airplane, whose value can be seen as the proportional norm of the profit, was used as the criterion of effectiveness. The type of airplane, cruising speed, range, passenger seating capacity and required size of the fleet were optimized. Twenty-seven different /218
projects were analyzed in this concrete problem. The results of analysis allowed conclusions to be drawn which are also not devoid in overall meaning: for routes 200-300 km in length, the most profitable is the vertical takeoff and landing (VTOL) airplane with lifting engines, calculated at 40 passengers; for routes 400-500 km long, the same airplane calculated for 80-120 passengers; for routes 800-1000 km long, a normal airplane calculated for 120 passengers. Variations of reverse formulation of the problem being examined deserve attention. They are the different type of the known transport problem, which is solved with methods of linear programming. For instance, in conditions of a combined transport network, finding the optimal variation of distributing existing airplanes of various models among the routes; for a given economic region with an airplane fleet on hand, finding the optimum variation of airport location, i.e. planning the optimum transportation network.

The problem of direct flight range was examined in work [3]. We will show the course of its solution, which is connected with the possibility for changing fares according to speed. For this, we first recall the concept of the commercial speed of an airplane:

$$V_k = \frac{L}{t_{cr} + t_a + t_i}.$$

[1] Luftfahrttechnik-Raumfahrttechnik, 1968, No. 11, pp. 267-273.

Here V_c is the commercial speed, i.e. average speed along the route with consideration of time for intermediate stops; t_{cr} is the cruising flight time, i.e. flight time over distance L with cruising speed V_{cr}; t_a is the additional time caused by maneuvering of the airplane near airports and by the difference in actual speed relative to the ground from cruise during climbs and descents; t_i is the time of intermediate stops.

Flights at long distances (5-6000 km and greater) can be accomplished in two ways: without landings, using heavy long-range airplanes and with intermediate landings, using airplanes of smaller dimensions. In the first case, due to a higher commercial speed, which will not be different from the cruising speed, the flight will be completed in less time, it will cost the passengers less, but operational organization introduces a smaller profit. This is explained by a decrease in the fare according to range, used in the domestic fare system, and by an increase in the cost per ton-km, which takes place in modern airplanes with an increase in direct flight range over 2000-3000 km [3]. So that the second variation of flight will be equivalent to the first economically, a decreased rate, considering the economic value of speed (18.2) must be established for it. A diagram of a solution to this problem allowing establishment of an optimum direct flight range, the number of intermediate stops and, consequently, dimensions of the corresponding optimum airplane is presented in Fig. 5.2. The problem of an optimal direct range for an airplane as a direct relationship to the problem examined in the sense indicated above, and was first examined in 1958 by A. A. Badyagin [3]. Minimum cost per ton-km was examined as the criteria of effectiveness, although it did not essentially effect the results of the solution. It was shown that L_{opt} depends little on dimensions and speed of the airplane, and for subsonic jet airplanes comprises approximately 900-1200 km. This value depends on the overall level of development of aviation equipment and, together with an increase in aerodynamic and weight perfection of airplanes and economy of engines, historically it will increase. /219

The way toward solving the third of the problems named above can be established using Fig. 5.3. If selection of the calculated range had an effect only on the amount of the cost per ton km, the optimum range would have been determined from the expression $S_{ABCD} \rightarrow \min$ (where S_{ABCD} is the area of figure ABCD), since with this the maximum value for the profit norm would have been provided. However, actual conditions of the problem are more complex, since selection of the calculated range also effects the dimensions and cost of the airplane, unique passenger flow and flight frequency are characteristic for routes of differing ranges (Table 6.2), and route speed and annual flight time increases as a function of range. Therefore, location of the optimal solution is made more complex. However, using electronic computer equipment, it generally does not comprise a great amount of work.

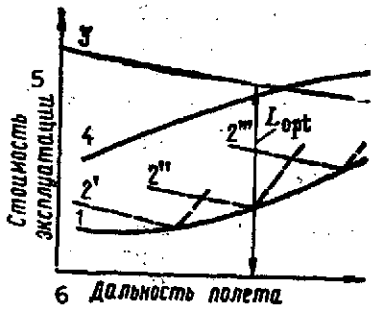

Fig. 5.2. On determination of the optimal direct range: 1. cost of shipping a set load on airplanes planned for different ranges; 2',2",2"'. cost for each of these airplanes; 3. rates (prices) for shipment; 4. special rates, considering the "price value" of time; 5. cost of operations; 6. flight range.

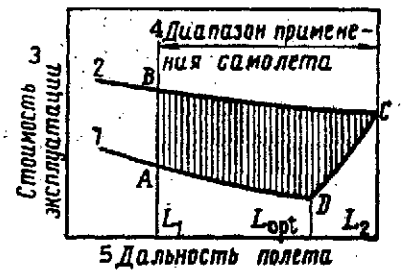

Fig. 5.3. On determining the optimal range of an airplane: 1. cost of shipments; 2. rate for shipments; 3. cost of operations; 4. Bracket for using an airplane; 5. flight range.

19.3. Optimization of working parameters. /220 Optimization of the working parameters of an airplane has always been given a great deal of significance, and individual problems of this type were examined very long ago. Such problems as, for instance, on the optimum length or sweep of a wing (solution of the weight-aerodynamic properties contradiction), of the optimal wing area (solution of the contradiction between speed, conditions of takeoff and landing and weight) and others. Interest in these problems is explained, apparently, by the fact that they are the ones which arise before airplane designers in the beginning. The mathematical formulation of a problem of this type is system (5.8). The group of functional liminations in the case examined are compiled of aerodynamic, weight and economic formulas. Inequalities characterizing the trajector upon failure of the engines, considering the allowable noise level, runway surface strength and dimensions, dimension sizes and available volume in the airplane, specific loads on the wing, emanating from conditions of flight at high and low altitude and others form the group of area limitations. Known parameters are the projected ones and usually the overall layout and engine characteristics.

Setting up the examined problem in the most general form to encompass only the major working paramters of an airplane is exclusively complex. Therefore, only its separate variations with a limited number of changed parameters (3-8) is usually selected. Among these parameters, the most interest is caused by: takeoff weight G_0, starting load on the wing p_0, number of engines, wing parameters (λ_i; $\bar{c}_i$; χ_i...), fuselage parameters (D_f; λ_f;...) and others [2].

At the present time, the number of parameters which must be considered in optimization of an airplane project is rapidly expanding. Among such "new" parameters, those of economics, thermodynamics, acoustics, equipment and control systems should be named first. While earlier they were selected or

considered after deterimation of the configuration and dimensions of the airplane and its weight now they must be considered during the process of these determinations. This planning system creates the prerequisites for future significant improvement in properties of an airplane and also for creation of principally new forms of an airplane. As an example, we will look at what possibilities are opened by consideration of control characteristics during selection of the basic dimensions of an airplane. It is known that from the point of view of frontal resistance and weight, it is advantageous to decrease the area of an airplane's empennage. This is, however, hindered by requirements of stability. If pitch and yaw dampers which artificially increased stability of the airplane were introduced into the control system, however, empennage area could be essentially decreased, and the weight of the airplane structure due to this and the accompanying decrease in loads on the tail part of /221 the fuselage, declines. The lightening can apparently reach 1% of G_0. Rough air overloads might also be sharply decreased in this same way, and the weight of the structure decreased correspondingly if special equipment were installed to decrease angles of attack of the airplane by means of controlling the rudders at the necessary moments in time.

A special system for controlling ailerons and rudders and the use of dampers could be used for combatting some forms of flutter in the wing and empennage. Calculations show that an appreciable savings in weight is achieved by this means, since flutter stability of a structure is usually increased by increasing the thickness of the skin or establishing loads. For maneuvering overloads, it is possible to use a special system for controlling distribution of air loads along the span of the wing to decrease the flexion moment. A sharp decrease in the weight of the wing can be achieved by this method.

Finally, with optimization of an airplane's parameters, it becomes necessary to consider the possibility of the appearance in the near future of totally new principles of control, particularly in the vertical plane. In connection with the increase in dimensions and the even sharper increase in inertia moments of airplanes which accompany them, their reaction to movement of the horizontal stabilizer progressively declines. In takeoff and landing configurations, this phemonenon can become inadmissible. Therefore, so-called "direct" methods of controlling the lift force of the wing are being developed (in using the usual horizontal stabilizer, influence on the lift of the wing is achieved indirectly, by means of previously rotating the airplane in the vertical plane). These direct methods might include: the use of a rotating wing, slats, flaps, spoilers, wing boundary layer control and others.

19.4. Constructions of minimal weight. Up to recent times, calculation of constructions for strength in all branches of technology was included only in checking strength (rigidity, stability). Development of structures was conducted on the basis of

practical experience and theoretical recommendations of the general character itself. Naturally, such a system caused significant overweighting in structures. With this, the problem of a structure which would under given conditions be the lightest one has always interested engineers and scientists. The first problem of this type (on beams of equal resistance) was examined during the time of Galileo. However, development of a sufficiently full theory for their solution became possible comparatively recently. Such outstanding scientists and engineers as Ye. O. Paton, V. G. Shukhov, and N. S. Streletskiy occupied themselves with problems of optimization of load-bearing structures. In aviation, one of the first to examine similar problems was N. G. Chentsov [60]. Now, the works of Soviet scientists A. I. Vinogradov, A. A Komarov, V. A. Komarov, I. M. Rabinovich, Yu. A. Radtsig, V. M. Ryabchenko, V. M. /222
Shalov and many others are widely known. The works of Polish professor Z. Wasyutinskiy, the works of the English and American scientists F. R. Schenley, V. G. Mix, G. Girard and others are known of the works of foreign scientists. (An overview of many of these works can be found in work [8].)

Modern interpretation of the problems examined has already moved outside the framework of only minimum weight, and therefore in a general case, the theories of optimal load-bearing structures (systems) in general is being spoken of. The most generalized formulation of these problems is conceived as a synthesis of a structure, i.e. selection of its diagram, dimensions, materials, cost and all other parameters. However, such a formulation is still too complex. Therefore, it is usually customary to examine the following problem: set external loads, basic dimensions, material and type of construction; an optimum structure corresponding to the max (min) object function must be found. The mathematical model for this problem is the same system (5.8). Equations of cost, weight or volume of material in the structure can be used as the purpose function. Equations of loading, strength and geometric relationships form the group of functional limiations. The group of area liminations can be compiled of inequalities describing the diagram, structural-technological, size conditions and others. During recent times, requirements for reliability, longevity or cost of the construction are also often examined among the limiting ones. Known parameters of the problem are properties of the materials, loads, basic dimension relationships and so forth. The sought parameters are the quantity, dimensions, shape and section of load-bearing elements, the volume or weight of the construction and others.

This type of problem is, for the time being, general. It provides for optimization of the system as a whole, i.e. determination of the number, spacing, shape and dimensions of all its elements. These problems can be called global or problems of macrooptimization. They are most complex and are still in the stage of study. Nevertheless, definite achievements have already been made in this direction [9, 14]. For separate problems in this direction (determination of the dimensions of torsion boxes, the

number and spacing of spars and ribs in wings and others) relatively simple solutions have been found [28, 66]. However, great results have for the time being been obtained in solution of individual problems touching not on the systems as a whole but only on their elements [66, 88]. Among these problems (they can be called local ones or problems of microoptimization) it is possible to name the following: planned section of optimal form; planned optimal sheet and coating (panels of the wing, fuselage and empennage); planned optimal rod systems (rods, braces, truss spars, ribs and others); planned optimal beams of constructions and frames (spars, ribs, frames and others) and; selection of optimal structural materials. /223

Study of the first two of the problems named above allowed not only formulation of general principles in selection of sections for work under torsion, flexion and shear, with and without loss of resistance, but also gave new quantitative criteria for selection of sections, which differed from previous ones, which were based on elementary representations of specific strength. Two new concepts lie at the basis of these criteria: the coefficient of section form and the index of intensity of loading (stress). For normal flat panels working under compressions, the coefficient of panel shape K_p (with consideration for total and localized loss of resistance) has the appearance

$$K_p = \frac{i}{b_s}\frac{\delta_0}{\delta_{pr}},$$

where i is the radius of panel section inertia; b_s is the distance between stringers; δ_0 is the thickness of skin; δ_{pr} is the presented panel thickness.

The criterion of effectiveness for section is the coefficient of form. The greater the coefficient, the more economic the utilization on the section and the lower the weight of the panel, all other conditions being equal. Fig. 5.4 shows examples of optimal values for coefficients K_p for panels of various types.

The index of intensity J for the panels examined, which determines the possibility for effective utilization of the material, has the appearance

$$J = \frac{P}{B_p L_p},$$

where P is the force compressing the panel; B_p is the width of panel (distance between the spars); L_p is the length of panel (distance between ribs).

Using the concepts presented, optimum critical stress of panels are described in the form

Тип панели 1	Т	▽	Y	⊤⊤
$K_п$ 2	1,02	0,985	1,185	0,81

Fig. 5.4. Coefficient of form for various types of panels.

Key: 1. Type of panel; 2. K_p

$$\sigma_{cr} = CK_p \sqrt{E_s} \sqrt{J}, \qquad (5.9)$$

where C is the constant, depending on the character of the butted fastenings of the panels; E_s is the secant modulus of elasticity of the material.

Eq. (5.9) allows solution of the most /224
varied optimization problems, and namely: finding the most suitable types of panels with high values for K_p (in particular, three-layer panels possess the maximum values of this coefficient); determining the most suitable dimensions of the panels (B_p, L_p), providing their minimum weight and; selecting the optimal construction materials. With low load intensities, as is visible from Eq. (5.9), the most effective are materials with high values of the relationship $\sqrt{E_s}/\gamma$ (here γ is the specific weight of the material). With high intensities, when phenomena of resistance loss ceased to be decisive, the advantage transfers to materials with high specific strength σ_{yc}/γ (σ_{yc} is the yield point of the material under compression). This criterion will also be the determining factor with low loading intensities, if phenomena of resistance loss succeed in neutralizing the high values of Kp (three-layer structures). The conditions presented allow the weight effectiveness of different materials in stringer panels to be compared depending on the intensity of their loading (Figs. 5.5 and 5.6).

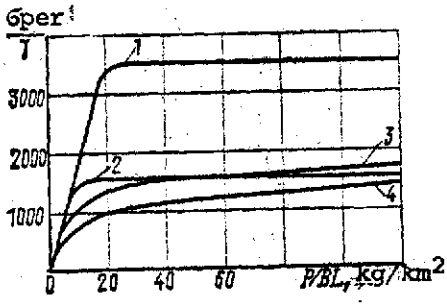

Fig. 5.5. Specific strength of stringer panels made of various materials under compression: 1. beryllium; 2. Elektron (σ_{yc} = 2800); 3. Duralumin (σ_{yc} = 5200); 4. titanium alloy (σ_{yc} = 7500).

The concept of intensity of loading has proved to be extremely convenient for its utilization in the most varied optimization problems. Thus, for instance, specific loading on a wing can be seen as an index of intensity of the total stresses of the wing, and, correspondingly, as one of the conditions predetermining its weight effectiveness. Pressure might serve as a similar index for a hydraulic system, voltage for an electrical system, and so /225
forth [27]. In a quantiative evaluation of the effect of the indices on weight, they can be seen as the volume of information "putting in order" the corresponding construction. This approach helps to clarify and analytically express many known weight dependencies of a statistical character (for instance, the dependency of relative weight of the structure on specific load on the wing, the relationship of the weight of the panel skin to the weight of the stringers and so forth).

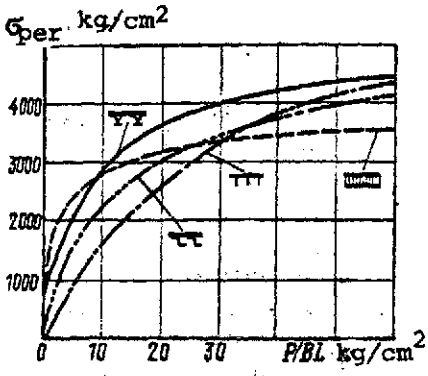

Fig. 5.6. Maximum permissible stresses of compression for panels of various types made of aluminum alloy (σ_{yc} = 5200).

The effectiveness of the methods of optimization examined is exclusively high. Thus, with global optimization of airframe components, the reduction in their weight by 10-20% is apparently possible. In a number of cases even greater results are possible. The weight of spars, beams, frames and ribs, planned with optimal methods, turns out to be three times less than if they had been accomplished out of elements having a constant section [32].

19.5. Evaluation of partial project solutions. The problem of increasing an airplane's effectiveness in the process of its development can be solved not only by means of optimization of parameters but also through evaluation of partial project solutions. The idea of this method of evaluation is not new. However, it was basically developed comparatively recently in the works of D. L. Tomashevich [53], Ye. A. Ovrutskiy, A. A. Badyagin [3] and others. The solution of similar problems was based on analysis of the conduct of purpose function with introduction of separate small changes in the airplane project. It is solved practically with new criteria, which are called equivalence of parameters. Their most important variations are cost equivalence ("cost of parameters," "loss from parameter" and "limiting feasible expenditures on improving the parameter").

The cost equivalent of a parameter represents the limiting increase in the cost of the airplane caused by a unit change of this parameter and the economically justified savings of means in the process of operation of the airplane with this change. With this, changes in the parameter are feasible if actual expenditures on the unit of this change do not exceed the cost of the parameter. Cost equivalence of the weight of an airplane, aerodynamic quality, reserve, reliability and so forth are known. Following determination, the cost equivalent of a parameter must be computed from conditions such that the value of the purpose function before and after introduction of the change in the airplane project remains unchanged. As was shown above, in analysis of these problems, the presented expenditures should be used as the purpose function. Therefore, the conditions expressed above must be written thusly:

$$C + E_{n\ [\text{normative}]}\frac{K_s}{A} = \text{const.}$$

We differentiate this expression according to parameters x_1 /226 and, transforming, obtain the expression for determining the cost equivalent of parameter x_1:

$$\frac{\partial K_s}{\partial x_i} dx_i = \left(-\frac{\partial c}{\partial x_i} \frac{A}{E_n} + \frac{K_s}{A} \frac{\partial A}{\partial x_i} \right) dx_i. \qquad (5.10)$$

For convenience in measurement, in formula (5.10) it is convenient to take $dx_i \sim \Delta x_i$, where Δx_i is a unit of change of the parameter (for instance, 1% of weight, quality, resistance and so forth).

Having cost equivalents, it is possible to find any other equivalent parameter relationships, for instance, comparing them with each other or expressing some parameters through others. It should be said that the concept of cost equivalent is not single-valued, since improvement of any parameter of an airplane can be taken advantage of in different ways. Therefore, two variations of the formulation of this problem deserve attention: G_0 = const, G_{cp} = var, i.e. improvement of parameters is realized for increasing commercial payload; G_{cp} = const, G_0 = var, i.e. improvement of parameters is realized for increasing the dimensions and weight of this airplane. The solution of both variations will lead to computation of values which were studied in detail by A. A. Badyagin [3]. the best known of these are the following $(\partial G_0)/(\partial G_n)$ -- derivative takeoff weight according to empty airplane weight, $(\partial G_0)/(\partial K)$ -- derivative takeoff weight according to average aerodynamic quality over a flight, $(\partial G_0)/\partial c_R)$ -- derivative takeoff weight according to average specific fuel consumption over a flight. Derivatives of takeoff weight are computed with the basic limitation of the examined problems -- unchanged flight data -- which also causes other limitations (p = const or S = const). Special, extremely precise initial formulas are needed for their computation. Due to the insufficient state of development of these, many impressions of these derivatives and their computed values published in the press remain disputed. In the theory of optimal planning, derivatives of takeoff weight occupy a special place, since in a number of cases they can be used instead of cost equivalent. These cases correspond to conditions through which the takeoff weight of the airplane can be seen as a criterion of its effectiveness (18.2). Among takeoff weight derivatives, the best known is the so-called coefficient of weight increase (coefficient of growth), which is defined as the relationship of the increase in takeoff weight to the initial change in empty airplane weight caused by it. It was examined in detail above (9.4). Computation of the value of this coefficient essentially depends on the character of the first change in the airplane's weight. While, for instance, the change in commercial payload weight is seen as the latter, the corresponding coefficient can be found according to the following approximation formula: /227

$$\frac{\partial G_0}{\partial G_{cp}} = \frac{0.8 - 0.9}{\bar{G}_{cp}}.$$

This coefficient is the largest out of all the others, since a change in commercial payload weight immediately affects not only the load, but also the volume of the fuselage. If the initial change in weight does not immediately affect the volume of the airplane, the corresponding weight gradient will be approximately twice as small as was determined above and it can be found according to the formula

$$\frac{\partial G_0}{\partial G_x} = \frac{0.8-0.9}{\bar{G}_{cp} + 0.5(\bar{G}_f + \bar{G}_{ef})},$$

where $\bar{G}_{ef}$ is the relative weight of equipment in the airplane fuselage.

It is not difficult to see that the method of equivalents does not replace, but only complements the general method of airplane optimization by means of determining its optimal parameters. However, together with this, this method allows solution of special project problems. For instance, it allows evaluation of effectiveness of such measures which are for the time being difficult to consider during optimization of parameters (measures connected with the use of new, more expensive construction material, technological processes, types of equipment and others). Moreover, this method allows evaluation of feasibility of airplane optimization tasks themselves. It permits evaluation of layout and arrangement solutions. Cost equivalents allow the comparative values of various parameters of an airplane to be established and the planner's efforts to be directed along the proper course. From their analysis, it follows in particular that effectiveness of an airplane is provided to an approximately equal degree by such factors as weight, aerodynamic and operational perfection and specific fuel consumption. Analysis of cost equivalents shows that technical politics directed toward creation of primarily inexpensive airplanes is doubtful. Airplanes which are more expensive but perfected in operation are more advantageous. This conclusion compels a review of the traditional attitude toward the technological level of construction and towards such production requirements as unification, normalization and so forth. It turns out that the advantages in production from these measures, if they are accomplished that the expense of weight, aerodynamics and other most important properties of the airplane, are covered over by disadvantages in operation. This is exactly why at the present time, the development of a new system of airplane planning can be observed, which primarily pursues specialization in construction. The USAF B-58, for instance, was created according to this principle. /228

Chapter 20. Mathematical Apparatus of Optimal Planning

20.1. Mathematical problems of optimal planning. After the mathematical model of an optimal planning problem is set up, the

question of the method of its solution arises. This is an independent and highly complex mathematical problem, whose difficulty in solution increases sharply with an increase in the number of parameters sought. In a number of cases the labor consumption in its solution can be decreased if the method, known in mathematics, of transferring from direct setup of the problem to its reverse is used. Thus, for instance, in optimization of airplane working parameters, instead of seeking the airplane's takeoff weight according to projected parameters (G_{cp}, L) a series of values for G_{cp} and L are first found for several fixed value of G_0. This is much simpler, since the basic mass of an airplane's characteristics are clearly expressed through G_0, and not through G_{cp} or L. In exactly the same way, in development of minimum weight structures, it is often significantly simpler to seek the load-carrying capability of the structure for a series of set diagrams and weight instead of seeking the diagrams and weights of the structure according to set loads (direct setup).

However, the basic difficulties in solution of system (5.8) are connected with more essential mathematical problems. Only in the simplest of cases, when the number of sought parameters is small, can classical methods of analysis be used. Special methods must be used significantly more often. Regardless of the fact that up to the present time a significant number of them have been worked out, research in this direction must continue. Some basic methods for solving system (5.8) are briefly described below.

20.2. Classical methods [16, 39]. The basic classical method is the normal method of extremes, based on utilization of the necessary condition of an extreme -- partial derivatives of the purpose function equal to zero. In this method, solution of system (5.8) boils down to solution of an auxiliary system:

$$\frac{\partial F}{\partial x_1} = 0; \quad \frac{\partial F}{\partial x_2} = 0, \ \ldots \quad \frac{\partial F}{\partial x_n} = 0.$$

This method possesses a number of peculiarities: the purpose function and its derivatives must satisfy the classical requirements of an extreme, i.e. be continuous, differentiated and not have points of inflection; extremes which can be on the borders of the area of existence of the purpose function cannot be determined by this method; determination of borderline extremes requires additional computations; determination of partial derivatives makes for great computational difficulties. /229

The method of Lagrange multiples is a means allowing treatment without solution of the coupling equation, which is often extremely complex or even impossible. Otherwise, it does not differ from the normal method of extremes. The idea of the method consists of the fact that conditions of the extreme are made up not for the purpose

function, but for its modification

$$F_0 = F + \lambda_1 Y_1 + \lambda_2 Y_2 + \ldots + \lambda_m Y_n,$$

where λ_1, λ_2 ... λ_m are the unknown Lagrange multiples determined during the process of solution.

If there are differential equations (for instance equations of motion of deformation) among the coupling equations, instead of the extreme of the purpose function, the extreme of the functional, i.e. the extreme of the integral of this function must be sought. In this way, the problem must be solved by methods of variational computation and will take on an especially cumbersome character.

On the whole, it should be established that the peculiarities of classical methods make their use for solution of system (5.8) in the general case inexpedient or even impossible.

20.3. Direct method [25]. In direct methods the search for an extreme is accomplished immediately, without using the necessary classical condition, which has an auxiliary character. This is where its name comes from. All these methods are repetitive. Their basic advantage is great economy, since instead of the system, only one equation -- the purpose function in its initial form -- is examined in them. Each of these methods has its deficiencies, on which we will not dwell. We will only note that at the present time, a great deal of research has already been accomplished so as to make these methods universal.

The simplest of them is scanning (blind search), i.e. sequentially looking over all possible variations of the solution accomplished with electronic computer equipment. This method does not present special requirements for the purpose function (it can be undifferentiated, have breaks and can be set down by the table method); there are no difficulties for it in determining extremes on the edges of the area of existence; the method allows extreme points to be examined very thoroughly, provides a possibility for establishing the character of the extreme (steep, slanting) and evaluating the effect of separate parameters on the purpose function, and; this method is the single reliable means for searching for the global extreme, i.e. the seepest among several. The expenditure of a great deal of machine time should be considered as one of its deficiencies. Therefore at the present time the use of scanning, if the number of optimized parameters is over 7-8, is considered unfeasible. True, with the appearance of higher-speed electronic computer equipment, possibilities of the method will be expanded. Time expenditures in scanning can be essentially decreased if limitation of the number of variations looked over is introduced. For instance, it is possible to conduct a search in several stages, at first with an increased search step, exposing

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probable areas of the extreme, and then with a more frequent step, but only in these areas. In this case, however, accuracy of the method declines. The prototype of the scanning method is the so-called method of parametric research, which is used in optimization without use of electronic computer equipment. The method consists of miscalculating a multitude of variations of the reverse problem, through which the character of the effect of different parameters can be understood. The results of calculations are depicted graphically, allowing development of the variation which, if not the optimum one, is close to it.

Of the remaining methods, the simplest, but not a very precise one, is the method of coordinate search (the Gauss-Zaidel method) [16]. The search for the extreme with this method is accomplished by means of sequentially examining a number of values for the purpose function, but not unsystematically, as with scanning, but being guided by the character of its change in each point in space according to each of the coordinate axes. For this, an arbitrary value is first selected for the purpose function. Then, its change is traced while changing only one of the parameters. A point at which a particular optimum in this parameter is observed is fixed. After this, the next parameter is investigated and so forth. A development of this method is the method of gradients. As is known, the gradient of a function having many variables is called a vector, which is directed toward the side of the greatest increase in this function and is defined by the expression

$$\operatorname{grad} F = \sum_{1}^{n} \frac{\partial F}{\partial x_i} j_i.$$

where ji is the single vector of the i coordinate axis. Determination of gradients gets rid of the necessity to accomplish a coordinate analysis at each point in space and provides a possibility for immediately determining the most profitable direction of the search (in the direction opposite that of the gradient). The method is relatively accurate, however it is very applicable only for objects with a purpose function of linear form. In other cases, the time of the search increases: steps which are too small are /231 not effective, and those which are too large decrease accuracy. A perfected form of the gradient method, which is widely used in practice, is the method of fastest descent. It differs from the previous one in that after the first working step, subsequent steps are made in the same direction, so long as the favorable change in the purpose function does not cease. At the new reference point, the gradient is again determined, and the search process continues further. This method leads to a decrease in the search time, although at the expense of accuracy.

The direct methods examined above are determined ones, since the order (algorithm) of the search in them is strictly determined. The

methods of chance search (the Monte Carlo method), based on the probability principle [46] has recently been greatly developed. In this method, the search program is formulated during its process on the basis of calculation of the most probable success. This method is adaptable to being self-taught. It provides an essential savings is search time, especially if the number of optimized parameters is high (over 8-10). True, in some investigations its advantages are subjected to doubt [45].

The highly widespread method for solving system (5.8) at the present time is the method of linear programming. However, it is used only in particular cases which are characterized by the following known conditions: the purpose function is a linear dependency of several parameters and; area limitations, also linear in character, must exist. However, the possibility of using the method is very great and, in particular, because some nonlinear problems can sometimes be reduced to linear ones. At the present time, a large number of different algorithms has been developed for solution of linear programming problems.

In conclusion, we note that any problem on optimization can be significantly simplified with a method which has been named "optimization relative to the selected prototype." In this case, parameters are varied near some earlier-selected values, whose nearness to the optimum one has already been established by some other means. The area of variation of the parameters in this can naturally be sharply contracted.

Chapter 21. Essence of the Problem

21.1. Reasons for deterioration of takeoff and landing characteristics. The reason for the deterioration of takeoff and landing characteristics is the increase in speed, with which increase, as has already been noted, the coefficient of profitability of airplanes increases, since their productivity and profits from operation increase and capital investments increase to a much lesser degree.

As is known, the maximum speed of an airplane can be determined according to the formula [5]

$$V_{max}=\sqrt{\frac{2p}{c_x\varrho_0}\cdot\frac{\bar{G}_e}{\gamma_e}}. \qquad (6.1)$$

Over the period from 1920 through 1960, the average values for the components of this formula in passenger airplanes changed in the following manner: c_x -- decreased by four times; γ_e -- decreased by 15 times, $\bar{G}_e$ -- decreased by two times, ρ_0 -- decreased by 3.5 times and p -- increased by 50 times up to 400-500 kg/m^2. Specific loading on the wing, as we see, plays the role of the most important factor in increasing flight speed. This is explained by the fact that its effect on the airplane is not limited only to speed. The greater p, the more compact the entire airplane, the less its surface and, correspondingly, its weight of construction. It can also be shown that with an increase in dimensions (and the development aviation, as has been noted, progresses exactly in this direction) the available space of an airplane changes proportional to the cube of the linear dimension of the wing. From here it follows that from conditions of optimal utilization of volume, specific loading on the wing must be changed proportional to the cube root from G_0. Practice supports the fact that airplanes are planned in accordance with this condition (Fig. 6.1). An increase in p in long-range airplanes is also expedient because by the end of the flight their weight turns out to be 1.5-2 times less than at takeoff due to fuel burnoff. The most important among the takeoff and landing characteristics of an airplane are, besides those earlier noted, liftoff speed during takeoff -- V_{lo}, landing speed -- V_{ldg}, the length of takeoff run, rollout and takeoff and /233 landing distances (Fig. 6.2). Two speeds are named which are proportional to the minimum allowable speed of the airplane near the ground, i.e.

$$V_{min}=\sqrt{\frac{2p_1}{\varrho_0 c_{y\,max}}}. \qquad (6.2)$$

(Here, p_1 -- specific loading on the wing during takeoff or landing.) From comparison of expressions (6.1) and (6.2) it follows that an increase in p must unavoidably lead to an increase in V_{min} and V_{ldg} and V_{lo}. With this, in a high-speed airplane, a decrease in c_x, besides the increase in p, will negatively tell on the value of V_{min}. Actually, this decrease is achieved primarily because of a decrease in the structural height of the wing, its lengthening and an increase in sweep. Meanwhile, all these measures will either negatively tell on $c_{y\ max}$ of the wing or decrease the effectiveness of normal mechanization. Together with an increase in V_{lo} and V_{ldg}, the lengths of takeoff roll and roll out will also increase, since these characteristics are directly proportional to the square of the corresponding speeds and, correspondingly, takeoff and landing distances. In this way, an increase in speed must objectively lead to a deterioration of takeoff and landing characteristics of airplanes (Fig. 6.3).

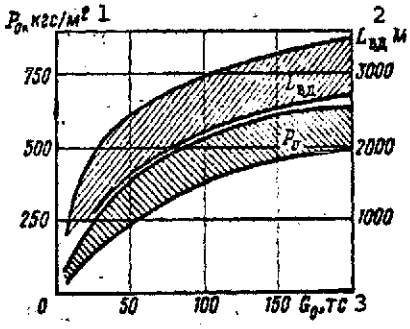

Fig. 6.1. Dependency of wing loading and takeoff distance length on takeoff weight.

Key: 1. P_0, kg/m^2; 2. Ltd, m; 3. G_0, t

21.2. The meaning of takeoff and landing characteristics. The tendency noted above has a number of undesirable consequences.

1. Pilotage is made more complex and safety is sharply reduced during takeoff and landing. Meanwhile it is known that nearly 80% of all accidents are observed in exactly these configurations and that the probability of an accident during landing is proportional to V_{ldg}^2. /234

2. The "weather minimum" of the airplane is decreased, i.e. limitations on takeoff and landing due to meteorological conditions increase and regularity andprofitability of flights decrease.

3. The dimensions and cost of airplanes increased. Meanwhile it is known that the cost of a modern airport is measured in tens of millions of rubles and depends most of all on the length of the runway (the main London port cost nearly 60 million dollars).

4. The dependency of airplanes on special airports decreases operability of aviation and restricts the sphere of its utilization.

5. An increase in flight speed will lead to an increase in maneuvering time in the air due to high flight altitudes, large turning radii, presence of limitations from the air traffic control system (ATC) and because of noise. The time of ground maneuvers also increases. All this on flights at short ranges decreases route speed noticeably.

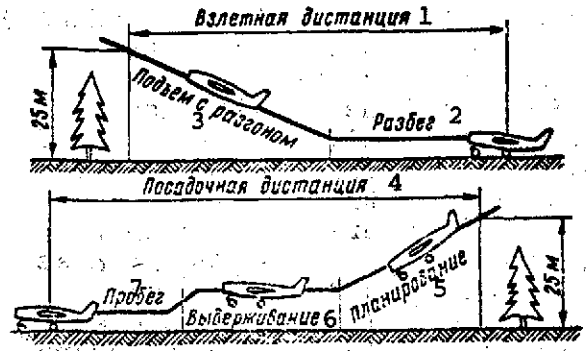

Fig. 6.2. Takeoff and landing distances.

Key: 1. Takeoff distance; 2. Takeoff roll; 3. Climb with acceleration; 4. Landing distance; 5. Glide; 6. Hold-off; 7. Roll out

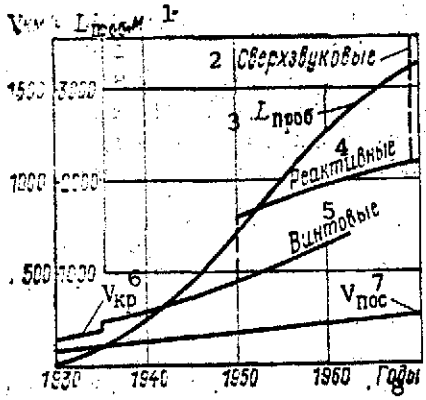

Fig. 6.3. Development of takeoff, landing and flying characteristics.

Key: 1. $V_{km/h}$ L_{ro}, m; 2. Supersonic; 3. L_{ro}; 4. Jet; 5. Propeller; 6. V_{cr}; 7. V_{ldg}; 8. Years

6. The necessity for locating modern airports at a distance from large settlements will lead to no less serious consequences. It is known that an airplane passenger's "ground time" necessary for travel from the place of his location to the airport and, upon arrival, from the airport to his destination presently consists of nearly 2 hours. On comparatively short routes (less than 1600 km), this time will exceed the actual flight time. As a result of this, the time "from portal to portal" increases and aviation fares increase incidentally (with consideration for additional expenses of the passenger for auxiliary transport). As was noted, the increase in cruising speed of airplanes operated on short distance routes over the last 20-30 years has not lead to an essential change in travel time "from portal to portal" (Table 6.1), and in some cases this time has even increased.

7. Overloading of modern airports causes particular delays in dispatching and accepting airplanes, which also causes a significant material loss.

The noted deficiencies in modern aviation transport are further aggravated by the following reasons: /235

The maximum overloading of all types of transportation, including aviation, is primarily felt on routes of comparatively short length (less than 700-800 km) (Table 6.2);

Operation of airplanes on short routes is close to unprofitable since the cost of operation here is high and rates, from conditions of competition with ground transport means, are comparatively low. With this, the high cost of flights over short distances is

explained by the fact that the small dimensions of a short-haul airplane make for its relatively low weight and aerodynamic perfection (influence of the so-called route effect), and also by the relatively high cost of the airplane itself and expenditures on its servicing;

TABLE 6.1. CHANGE IN FLIGHT TIME ON THE NEW YORK-BOSTON ROUTE (DISTANCE APPROXIMATELY 300-320 km)

Year	Flight time in min				Speed in km/h		
	En route	Maneuvers in the air	Maneuvers on ground	Total	Cruising	Route	"From portal to portal"
1940	62	5	5	72	290	250	105
1955	30	10	10	50	560	360	122
1965	20	10	20	50	890	360	122

Due to the insufficiency of special short-haul airplanes, it is often necessary to operate airplanes calculated for long ranges on short distance routes, and the cost per ton-km on these routes proves to be higher than it might be with a special airplane. Besides this, transportation of a comparatively small group of people (no more than 30-50 persons) is frequently necessary on short routes. Therefore, normal loading of large airplanes is not provided on these routes. Overcoming the deficiencies noted above is possible in two, principally different, directions.

TABLE 6.2. DISTRIBUTION OF THE OVERALL PASSENGER FLOW AMONG ROUTES OF DIFFERENT DISTANCES (AVERAGE STATISTICAL WORLD DATA)

Distance of routes, km	Relative passenger flow
200	13.5
200—500	45.0
500—1000	19.0
1000—2000	12.0
2000—3000	6.0
3000	4.5
Total	100.0%

The first is connected with a further increase in flight speed. /236 However, the possibility of utilizing flight speed as an economic factor in subsonic aviation after its achievement of numbers M = 0.8-0.9 is in essence exhausted. With these M numbers, a maximum so-called parameter of speed km/c_R is observed (Fig. 6.4). Therefore, increasing cruising speed of a modern jet airplane by 50-60 km/h does not further affect its range and route speed. Only a significant increase in speed and flight range can have a perceptible economic effect. The realization of this possibility is connected with creation of supersonic passenger airplanes (SST). However, it is apparent that these airplanes cannot solve the problem of short routes.

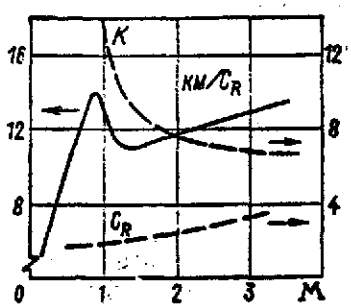

Fig. 6.4. Dependency of the speed parameter on the M number.

The second major direction in the development of modern aviation is connected with an increase in cruising speed, and the speed "from portal to portal." It rests on the primary improvement of takeoff and landing characteristics of the airplane. The first preliminary step in this direction, made several years ago, consists of creation of jet airplanes with short and medium ranges (BAC 1.11, Boeing 727, "Trident," DC-9, "Super Caravelle," Tu-124, An-24 and others. They differ from their predecessors -- long-range airplanes -- in their smaller dimensions and weight, and chiefly, extensive mechanization of the wing, which allowed their usage at small local airports, was not used earlier.

The next step in this direction consists of creation of principally new types of airplanes: short takeoff and landing (STOL) and vertical takeoff and landing (VTOL) airplanes [44, 47]. Before moving to examination of them, however, we recall the basic means for improving the takeoff and landing characteristics of an airplane (Table 6.3).

Chapter 22. Means of Improving Takeoff and Landing Characteristics /237

22.1. Means affecting acceleration of the airplane. These means decrease the length of takeoff and landing roll of an airplane (and correspondingly, the takeoff and landing distances) by affecting its acceleration, without changing V_{min}.

For decreasing the length of takeoff roll, it is possible to:

- Increase the power-to-weight ratio of the airplane during takeoff by means of selecting a corresponding type of engine or temporarily boosting it. Thus, for instance, it is known that propeller and turboprop power units provide significantly higher thrust than normal jet ones at low speeds. Boosting of engines /238

TABLE 6.3. METHOD OF IMPROVING TAKEOFF AND LANDING CHARACTERISTICS OF AIRPLANE

Technical principles	Technical means			
	Acceleration		Specific load on the wing	cy max of the wing
	During take-of roll	During roll out		
Selecting the parameters of the airplane	Increasing power-to-weight ratio	--	Decreasing specific loading	Selecting profile and shape of the wing
Creation of additional horizontal thrust	Decreasing resistance of the airplane and wheels, boosting engines, using accelerators, catapults, ramps and booster engines	Using arrestors, parachutes; aerodynamic and wheel brakes, engine reversing, ground braking means	--	--
Mechanization of the wing	--	--	Increasing S of the wing during take-off and landing	Normal mechanization, slotted; changing sweep
Activation of the boundary layer	--	--	--	Boundary layer control systems, control of circulation, turbulators
Creation of vertical thrust	--	--	Rotating the thrust vector, use of lifting engines and devices	Control of circulation

is achieved through increasing the number of revolutions, combustion of additional fuel or injecting water or special mixtures and allows engine thrust (power) to be temporarily increased during takeoff by 15-25%. Afterburners increase jet engine thrust by 25-40%;

- Using starting accelerators which are dropped after takeoff. The increase in power-to-weight ratio with this can reach 100%;

- Decreasing the aerodynamic resistance of the airplane. For this, since at low speeds the major form of resistance is induction, the length of the wing should be increased;

- Catapult the airplane with special devices. They may be guides along which a carriage with the airplane installed on it moves, or devices towing the airplane by its gear;

- Lauch the airplane with inclined starter ramps. The lifting force required for takeoff with this would be created by both the main engines and by accelerators.

Means for braking an airplane during landing include:

Wheel brakes. This type of braking decreases roll out length by approximately 50-60% and is a necessary accessory for any modern airplane. To increase the power capacity and reduce the weight of brakes, they are presently manufactured using beryllium, metal ceramics and other materials. Artificial cooling of them is also used. To avoid skidding the brake wheels, reducing the effectiveness of braking, automatic brake release devices, which engage upon a sharp decrease in wheel rotation speed, are used. These devices also decrease tread wear and increase operational safety.

Braking parachutes. This type of braking is highly effective. Parachutes are, however, dangerous in the presence of a crosswind, cumbersome, expensive and short-lived. Therefore, in civilian aviation they are usually used as an emergency means. Instead of parachutes, it is possible to use aerodynamic brakes, which are surfaces on the fuselage or wing which are slanted out during landing. Due to the small area of these brakes, their effect is essentially less than that of parachutes.

Spoilers (interceptors) are an effective means for braking an airplane. Besides increasing C_x, they also decrease C_y of the wing, with which greater pressure of the airplane on the runway and greater effectiveness of the work of the wheel brakes is provided.

One of the most modern methods for braking an airplane is reversing the thrust of the propellers or engines. Reversing provides braking which does not depend on the speed of the airplane and peculiarities in the surface of the airport.

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So-called "booster" engines have been proposed recently. This /239
engine has small dimensions and weight and is engaged only during takeoff and landing. During takeoff it works as an accelerator, and during landing it is rotated by 180° and creates a negative reversing thrust (for more details see 4.4 and 6.2).

Besides the "on-board" means for braking, "ground" means are used. These include nets or cables that the airplane engages during landing, after which these devices can engage other braking devices into operation: hydraulic cylinders, loads and so forth. Special retarding types of pavement for the last sections of runway have also been proposed recently. Ground braking is on the average twice as effective as on-board braking.

It is not difficult to see that the means examined have the following inherent deficiencies: since they do not affect the value of V_{min}, they do not reduce the overall loading of the gear and the entire structure of the airplane; due to conditions of comfort and safety, many of them are unusable for passenger airplanes; due to the necessity for using separate means for takeoff and landing, the complexity and weight of the airplane increase. A decrease in runway length due to these means is accompanied by complexity of the airplane and airport equipment.

22.2. Means effecting specific wing loading. A natural means for improving takeoff and landing characteristics of an airplane is control of the area of the wing. This idea is used in many forms of modern wing mechanization. Great structural and weight difficulties, however, stand in the path of its widespread usage. Nevertheless, several airplanes with this type of wing mechanization have been built in the past [52]. Experience in the creation of folding wings and wings with variable sweep testifies to the fact that the practical embodiment of similar, seemingly fantastic ideas is not at all eliminated. Thus, for instance, flight tests were begun relatively recently on the "Beechcraft 18" airplane with a changeable span wing, which allowed not only the area but also the induction resistance of the wing to be affected (see p. 60).

Decreasing wing loading during takeoff and landing is also possible with an incidental means through creation of additional vertical thrust at the corresponding moments in time. The following variations of solution of this problem are known:

- Rotation of the entire engine or tailpipe (in jet engines). Since the horizontal component of the thrust is proportional to the cosine of the angle of rotation, and the vertical component is proportional to the sine of this angel, a comparatively small rotation of the thrust vector is sufficient;

- Use of special lifting engines;

- Use of turbofans driven by gases which are exhausted from the main engines;

- Deflection of the wake stream from the propeller engine or turboprop engine with a high coefficient of by-pass using a system of powerful flaps (Fig. 6.5). /240

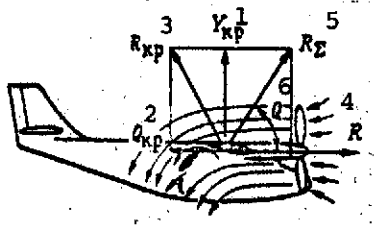

Fig. 6.5. Diagram of forces acting on an airplane with control of the wake stream from propellers (during takeoff):

Key: 1. Y_{cr} -- lift force; 2. Q_{cr} -- resistance; 3. R_{cr} -- resultant aerodynamic force; 4. R -- propeller thrust; 5. R_{Σ} -- resultant of all forces; 6. Q -- angle of inclination of resultants.

22.3. Theoretic bases of increasing $c_{y\ max}$ of the wing. Before examining construction means for increasing $c_{y\ max}$ of the wing, we will recall some theoretic information.

The value of $c_{y\ max}$ of a section of a wing passing through an ideal fluid, according to the theorem of N. Ye. Zhukovskiy, is proportional to the relative curvature of the section. However, under conditions of actual streamlining, the value of $c_{y\ max}$ is also affected by the appearance of the boundary layer and the phenomenon of stall connected with it. The problem of increasing $c_{y\ max}$ of the wing under these conditions consists of preventing early stall. For this, first of all, the value of the basic characteristics of the body's streamlining (criteria of similarity), the Reynolds number (Re) and the M number should be kept within the necessary limits. As is known, the turbulent boundary layer which arises with large Re numbers, has a large reserve of kinetic energy and is less susceptible to stall than a laminar layer. Therefore, to increase $c_{y\ max}$, the Re number of the section should be increased, for which the chord of the wing is increased. The M number, as is known, evaluates compressibility of the air, which affects the overall picture of pressure, speed and temperature near the streamlined body. In particular, waves of compression cause sharp fluctuations in pressure along the chord of thesection (longitudinal pressure gradients), which promote stall. Therefore, an increase in the M number above 0.3-0.4 will usually lead to a drop in $c_{y\ max}$ of the wing section. During takeoff and landing, due to wind gusts, initial air turbulence and steep maneuvers, localized critical M numbers can be achieved with flight M numbers still lower than 0.15-0.2. To prevent this phenomenon, it is necessary to select corresponding profiles. A number of measures especially pursue the decrease in longitudinal pressure gradients. These include: use of the optimal values $\bar{c}$ = 0.12-0.18; warping the nose and tail of the section, which delays nose and tail stall (optimal radii for warping the nose in a

section of moderate thickness are 10-12%, which allows a $c_{y\ max}$ to be increased by 50%); locating the maximum section thickness closer /241
to the nose by approximately 25-30% of its chord and others. The latter group of measures used to increase $c_{y\ max}$ on the wing is connected with the aerodynamic design of the wing as a whole and is aimed at preventing early localized stalls. These include: selection of optimal wing taper to increase the Re number of the section lying in its central part, because stall on the wing arises first exactly there; optimal selection of types of sections along the span of the wing; changing the established angles of attack of the sections along the span ("twisting" the wing) and; careful design of the shape of fairings, tip fairings and other elements of the wing. On a swept wing, besides this, fences, "grooves," changeable sweep along the leading edge and other measures are used.

We note that in modern sections, critical angles of attack, depending on the shape of the section, M number and other factors, have the value α_{cr} = 8-18%. The value of $c_{y\ max}$ fluctuates from 0.7 to 1.7-1.75. Lesser values relate to thin, symmetrical, i.e. "high-speed" sections and low Re numbers. Greater ones relate to the so-called "load-bearing" sections, i.e. relatively thick ones with high relative curvature and large Re numbers.

22.4. Mechanization of the wing. Due precisely to mechanization, takeoff speeds of modern airplanes do not exceed 300-350 km/h, and landing ones 240-290 km/h, while maximum speeds reach 2000-3000 km/h and greater. In other words, the range of speeds in modern airplanes is equal to 7-10, while in the first airplanes it did not differ much from 1. We note incidentally that in STOL airplanes, the speed range is increased up to 14-20.

The idea of wing mechanization consists primarily of the possibility for changing wing profiles which were calculated for high speeds into those suitable for flight at low speeds. Actually, high-speed sections must be thin ($\bar{c}$ < 0.14), have little or zero curvature, a relatively sharp leading edge and maximum thickness shifted by 50% of the chord. Requirements for low-speed "high-lift" sections, as is known, are in the reverse order. Profiles designed for high and low speeds are schematically depicted on Fig. 6.6, and ways of solving the contradiction between these pro- /242
files with normal mechanization are shown. Its simplest forms are the deflection of the nose and tail portions of the wing downward (simple flaps or panels), thereby increasing the relative curvature of the section.

Possibilities of the simplest wing mechanization are extremely limited, more so because the effects of deflecting the nose and tail parts of the wing are not summary, but only complement each other: tail separation does not necessarily lead to the achievement of no effect on the nose of the section and vice versa. Therefore, simple mechanization is encountered relatively rarely at

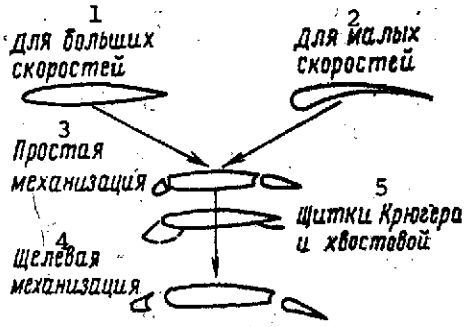

Fig. 6.6. Development of types of mechanization.

Key: 1. For high speeds; 2. For low speeds; 3. Simple mechanization; 4. Slotted mechanization; 5. Kruger and trailing edge panels.

the present time, although effective means of this mechanization which are applicable to the thin wings of high-speed airplanes (Kruger panels, increasing the area and curvature of the wing and; turbulators -- small plates installed perpendicular to the surface of the wing for activation of the boundary layer) have been developed in recent times. Attempts were made even in the first years in the development of aviation to perfect simple mechanization by means of affecting the boundary layer, which led to the appearance of modern slotted mechanization, i.e. slats and slotted flaps. Their action is based on direct utilization of three principles: increasing section curvature and wing area and transmitting additional kinetic energy to the boundary layer by routing here through slots formed during operation of the mechanization, from the lower surface of the wing above the area of increased pressure to the upper one. The idea of this mechanization was expressed and founded in 1910 by S. A. Chaplygin. It was formulated for design in the 1920's.

Slats are divided into fixed, automatic and controlled. The latter are presently most frequently used. On very thin wings, it is advisable to replace them with Kruger panels due to structural and weight considerations. Characteristic in the action of flaps is the fact that together with increasing $c_{y\ max}$ (by approximately 50%) the critical angle of attack is also increased (also by 50%). Besides this, a slat increases c_x of the wing. All this makes utilization of slats as an independent form of mechanization more difficult, and they are used only in combination with mechanization of the trailing edge of the wing. Slotted flaps are divided into extension (single-slot) and telescoping (two- and three-slotted). In multi-slotted flaps, the effect of the additional slots is used to prevent stall at the flap itself, which increases its working capacity up to high angles of deflection. The action of flaps is based first of all on increasing curvature of the section. Therefore, the critical angle of attack during action of the flaps is not increased.

The construction of flaps is relatively complex and leads to a significant increase in the weight of the wing (up to 20-30%), which forces, in evaluating the feasibility of their usage on passenger airplanes, the performance of corresponding analysis. /243

A new form of wing mechanization appeared comparatively recently -- changing the angle of sweep. In an airplane with a variable sweep wing, it is set depending on the flight configuration. As is known, the value of the lift force of the wing depends on the effective speed on the onrushing stream V_{eff}. With zero sweep, V_{eff} coincides with the speed of flight. With a sweep different from zero, $V_{eff} = V \cos \chi$ and the lift force of the wing is correspondingly smaller. Besides this, the characteristics of longitudinal stability and controllability are deteriorated with a swept wing. During takeoff, landing and low-speed flights, a variable sweep wing is set at zero sweep and has a high lift force and the best characteristics of stability and controllability. Conversely, during flight at sound speeds, an angle of sweep greater than zero is provided. With this, the wave resistance of the wing is decreased and the deterioration in its lifting properties is compensated by the high flight speed. Creation of the variable sweep wing presents many problems connected with flight stability and controllability and with the construction of the wing itself. Suffice it to say that its weight can be 30-40% greater than in the normal wing. It is doubtless, however, that variable sweep is a highly promising means for improving airplane data.

22.5. Boundary Layer Control (BLC). The idea of active BLC (or simple BLC) consists of imparting additional kinetic energy to the boundary layer through special sources of energy. This idea has been long known. In 1904, L. Prandtl experimentally showed the effectiveness of the influence of boundary layer suction on the flow of liquid in tubes. In 1926, B. N. Yur'yev proposed a wing with a movable surface. In 1938, a similar construction was experimentally accomplished by Favor. Experiments with blowing and suction of the boundary layer on a wing were especially actively conducted after the Second World War. However, before the appearance of turbojet engines, the creation of a BLC system on airplanes remained problematic, since additional pumps or compressors with a complex drive from the main or special engines, heavy channels and other devices were required for this. And without this, the high weight of piston power units did not allow additional weighting, and the weight strain from the propellers had a negative effect on the work of the system. Conditions for practical usage of the BLC system on an airplane arose only in connection with the appearance in the mid-1940's of jet engines -- engines with low specific weight, and allowing compressed air or exhaust gases to be obtained directly from the engine. On the other hand, it is impossible not to note that high-speed jet aviation itself became interested in such a /244
powerful means as BLC to the maximum degree. The appearance of turbofan engines with high coefficients of by-pass, allowing very great quantities of air to be diverted from the engines opened new perspective for BLC systems.

For the time being, BLC is relatively widely used only on small military airplanes. However, everything points to the fact that BLC is a most important prospective means for passenger airplanes

and its introduction into civilian aviation has become an urgent necessity. Different variations of BLC systems are most often used in combination with normal mechanization. With this, BLC on the leading edge of the wing acts similarly to the slat and makes it unnecessary, while BLC in front of a flap increases its effect and allows flap arrangement to be simplified. Systems with blow-off and with suction of the boundary layer are possible. The first were the most widely used because they are simpler than the suction systems, although the latter are thought to be more economic. Besides this, the blow-off system possesses one more essential feature. Boundary layer suction removes the decelerated boundary layer and thereby restores the quantity of its movement. Naturally, the latter in this cannot exceed the quantity of movement of the undisturbed flow, and $c_{y\ max}$ cannot surpass the value defined by the theory of potential streamlining. Blow-off of the boundary layer creates some reaction thrust, and also imparts a quantity of movement to the boundary layer which exceeds the value defined by the theory of potential streamlining, and works to increase circulation around the profile (the so-called "over-" or "supercirculation" phenomenon). With this the value of $c_{y\ max}$ can exceed "normal" values and in any case will be greater than with suction.

Suction can be accomplished through slots, or a perforated or porous skin on the upper surface of the wing. Suction distributed along the surface is more economic than discrete (slotted), and is used more often. Suction from the front edge of the flap is more economic than suction from the leadingedge of the wing, but its construction is more complex. The following general deficiencies in the construction of systems with suction should be noted.

The manufacture of skins is complex, it increases the weight of the wing; installation of special compressors with drive from main or special airplane engines is required. Pipelines of the system must possess high hermetic seal, since a reserve in suction is required to be sufficient so that the system is not sensitive to pressure pulsation, which takes place on the surface of the skin. Therefore, a pipeline which is calculated for this loss of stability turns out to be heavy.

The danger exists of contaminating and icing the slots and holes in the skin, and also sucking water into the system.

Intensity of pumping is usually evaluated with the coefficient /245 of flow rate [38]:

$$c_Q = \frac{Q}{SV},$$

where Q is the volume of air sucked off in 1 sec (m^3/sec).

The effect of blow-off depends not only on the volume of air, but also on its speed. Therefore, the intensity of blow-off is evaluated with the coefficient of impulse of the quantity of jet-stream movement:

$$C_{\mu} = \frac{mW_s}{qS},$$

where m is the mass air flow per second, W_s is the speed of stream at the nozzle tip, q is the velocity pressure.

With blow-off the ejection effect, which allows the impulse of the stream to be doubled, can be used in the sprayers.

Introduction of BLC systems on modern airplanes is tied to the necessity for solving a number of complex problems. These include the creation of corresponding power units, the development of the theory for calculating boundary layer, the problem of reliability and safety on flights at low speeds, the problem of weight, and, finally, the problem of economic effectiveness.

An airplane with a BLC system must have engines which allow the necessary quantity of compressed air to be diverted from the compressors without an essential loss in thrust (no more than 3-5%). Not all types of turbojet engines presently satisfy this requirement. Besides this, the problem of assuring functioning of jet engine intake devices at high angles of attack arises. It can be solved with special slats installed at the entrance in the air intakes. When landing an airplane with BLC, it is necessary to solve the contradiction between the necessity fordecreasing the thrust along the center line, but increasing it to provide operation of the BLC system. With installation of several jet engines on an airplane, the air diversion manifolds must be connected together, so as to provide identical characteristics of the system on both wings and provide its working capacity upon the failure of any engine. Safety upon the failure of the entire BLC system must also be provided.

In airplanes with BLC, the problems of pilotage at low speed with a strongly deflected stream and in the immediate proximity of the ground, which essentially affects the work of the system, are relatively complex. Flight in these conditions is characterized by disruption of all types of stability and controllability. Therefore, as a rule, automation of control of the airplane and the use of various special devices are required. In particular, to increase characteristics of longitudinal stability and controllability, slats or a BLC system are installed on the horizontal stabilizer. The use of a BLC system on an airplane, according to data on hand, /246 increases empty airplane weight by approximately 2-4% of the G_0, if suction is used, and by 1-2% of the G_0 if blow-off is used. These figures, as can easily be seen, are extremely significant.

22.6. Control of wing circulation. If a relatively powerful blow-off above the flap is provided on the trailing edge of the wing, $c_{y\ max}$ of the wing can reach values of 7-7.5 and even greater. The idea of this method of increasing lift force of the wing was set forth in the 1950's and received the name reaction (stream) flap or circulation control (Fig. 6.7). The action of the reaction flap emanates from the BLC principle. However, qualitatively it acquires a new character, since the reaction stream creates a thrust and a vertical lifting component. With this, the thrust of the stream can compensate a loss in engine thrust. Interacting with the stream rushing against the wing, the reaction thrust also rearranges the section streamlining picture, creating very high suction above the wing. The described phenomenon, as was already noted is called over- or supercirculation. The intensity of a reaction flap is evaluated in the same way as for a BLC system, with the coefficient of impulse of the quantity of stream motion. The use of a reaction flap on an airplane is accompanied by great construction difficulties. The significant displacement of the focus and center of pressure during operation of the flap toward the rear edge of the wing is also a serious deficiency in the reaction flap. High power engines are necessary for operation of a reaction flap and during landing they must be reversed. One of the variations of a reaction flap is a stream flap with an internal canal. In this flap, the strain is thrown off through a channel which forms the upper and rear parts of the flap. Diversion of air and loss in thrust of the main engine with this is relatively significant. However, thrust, due to the flap, is practically not only restored, but also increased, which is explained by the ejection effect of the external air. Table 6.4 presents comparative data on effectiveness of various mechanization means and BLC systems. /247

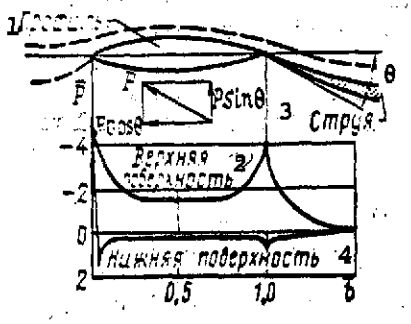

Fig. 6.7. Diagram of pressures and reaction forces acting on a section with a reaction flap.

Key: 1. Section; 2. Upper surface; 3. Stream; 4. Lower surface.

Chapter 23. Short Takeoff and Landing (STOL) Airplanes

23.1. Definition, classification and planning requirements. As was already noted, airplanes which, possessing high cruising speeds and at the same time having a low value for takeoff and landing distances have come to be called short takeoff and landing airplanes. Short takeoff and landing distances were at first taken to be a value on the order of 150 m with an obstacle height of 15 m. It was later explained that an airplane created according to these requirements would not differ from an airplane of a higher class -- vertical takeoff and landing airplane. Therefore, the takeoff and landing distance for STOL airplanes will be increased first up to 300-400,

and then up to 500-650 m, depending on the purpose and dimensions of the airplane. At the present time, short takeoff and landing (STOL) (150 m < L_{td} < 350 m) airplanes and accelerated takeoff and landing (ATOL) (350 m < L_{td} < 650 m) airplanes are differentiated. We note that for normal airplanes, the length of the runway in the majority of cases exceeds 1200 m, and the value of the takeoff distance comprises no less than 1800 m. The landing speed of STOL airplanes is approximately half that of a normal airplane and comprises 100-110 km/h.

TABLE 6.4. APPROXIMATE EFFECTIVENESS OF METHOD OF INCREASING c_y t/o

Type of mechanization	$c_{y\ t/o}$ ($c_{y\ t/o} < c_{y\ max}$)
Deflecting leading edge	1.2—1.4
Slat	1.5—1.6
Flap	1.7—1.8
Slotted flap	2.0
Double slotted flap	2.6
Deflection of wake stream	3+0.8 C_μ (4,5)
Boundary layer blow-off (thrust loss no more than 5%)	3+30 C_μ (5.0)
Stream flap (thrust loss no more than 30%)	5+1.5 C_μ (6,5)
Reaction flap (thrust loss no more than 30%)	5+2.5 C_μ (7.5)

As a type, STOL was composed in the 1950's. At the present time, several models of STOL airplanes are already being built. A large number of plans is in the stage of development (Table 6.5). Some STOL airplanes are calculated for use in areas with unfavorable airport conditions, especially high requirements are outlined for them with respect to the landing gear, which must possess high cross-country capability and the capability for rapid exchange (for instance, of wheels for skis). Others are intended for operation on short distance aviation routes (up to 1600 km). Airplanes for this purpose must relieve ground transport means and speed up communications. They will be operated not only from normal, but also from nonstationary airports, constructed even within city limits, in yards, on bridges, pontoon installations on the water, and so forth. Special requirements are outlined for airplanes of this purpose with respect to reliability, safety and comfort, both for passengers and for the population, and chiefly, as was already noted, with respect to profitability. /248

23.2. Principles and problems of planning. The creation of STOL airplanes is an exclusively complex engineering problem, which

TABLE 6.5. DATA OF SOME CIVILIAN STOL AIRPLANES

Airplane	G_0, t	Engines	$\frac{V_{cr}}{V_{min}}$ km/h	L km	r_0 kg/m²	Number of passengers	$L_{t/o\ roll}$ m	$L_{roll\ out}$ m	$\frac{L_{t/o\ ed}}{L_{ldg\ ed}}$ m	Means for improving takeoff and landing characteristics
Brege 941 (France)	26.5	Turboprop engines 1500 ehp ×4	$\frac{425}{40}$	5000		40—50	$\frac{60}{35}$		$\frac{350}{270}$	Deflection of stream from large diameter propellers using double slotted flaps
DHC-4 "Caribou" (Canada)	13.0	Piston engines 1200 hp ×2	$\frac{290}{100}$	1800	150	30	$\frac{220}{200}$		$\frac{360}{380}$	Same
DHC-7 (Canada) (project)	13.5	Jet engines 735 ehp ×4	$\frac{435}{}$	1850	230	40	—		$\frac{487}{366}$	Stream flap
Fiat G-222 (Italy)	20.3	Turboprop engines 2775 ehp ×2	$\frac{450}{}$	—	200÷250	~40	$\frac{340}{}$		$\frac{600}{390}$	Deflection of stream from large diameter propellers using flaps. Boosting of engines
Boeing-737 (USA) (project)	41.0	Jet engines 6350 kg ×2 lifting turboprop engines 3200 hp ×4	$\frac{910}{156}$	2000	—	100	—		Runway 610 m	Mechanization of wing and lifting engines

includes: selection of the layout and basic parameters of the airplane, selection of the type and number of engines, solution of problems of flight and technical operation, construction, strength, weight and evaluation of the effectiveness of the airplane as a whole. We will remain on the basic aspects of these questions.

1. Existing STOL airplanes as a rule have small dimensions. This is explained for the following reasons.

As was already noted, improvement of takeoff and landing characteristics is most real for airplanes used on short distance routes (less than 1600 km), where flights are frequent and the number of passengers per flight is small (Fig. 6.9).

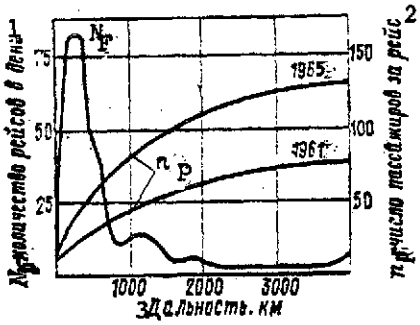

Fig. 6.8. Features of routes of different distances.

Key: 1. N_f -- number of flights per day; 2. N_p -- number of passengers per flight; 3. distance, km

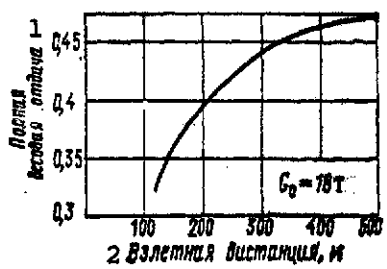

Fig. 6.9. Load ratio of STOL airplane.

Key: 1. Total load ratio; 2. Takeoff distance, m

As was shown above, with an increase in the dimensions of the airplane, specific loading on the wing increases in conformity, and takeoff and landing characteristics deteriorate (see Fig. 6.1). Consequently, the difficulties in creation of an STOL airplane increase with an increase in its dimensions.

This noted phenomenon is, however, doubtless transient, since the number of passengers per flight on all routes increases rapidly over the years. According to data from foreign press, the appearance of an STOL airplane with /250 relatively large dimensions is expected in the near future.

2. In order to assure the basic idea of STOL, the utilization of the fullest possible complex of all those measures which were examined above (in Chapter 22) is required.

In particular, an increase in the thrust-to-weight ratio of STOL airplanes is dictated by the fact that airplanes of this type are especially sensitive to reasons causing an increase in resistance, albeit temporary and small, during takeoff and landing: deflection of the flaps at large angles, unfavorable characters and conditions of runway surfaces and others. According to data from the foreign press, in modern fighters, $\bar{R}_0$ = 0.5-0.7, in transport airplanes $\bar{R}_0$ = 0.2-0.34, and for the

STOL airplane, the most commonly accepted value is $\bar{R}_0 = 0.35-0.5$. However, since the high thrust-to-weight ratio for airplanes of the type examined in flight is superfluous, and simply harmful from the point of view of weight, increasing the thrust at the start is often achieved through various means of boosting. The booster engine used on the DeHavilland Canada (DHC) "Otter" is interesting from this point of view (see p. 226).

3. The best engine type for STOL airplanes is the turboprop, since it provides the maximum thrust at low speeds. This type of engine also allows the effect of wing mechanization to be increased. However, in cases where a BLC system is installed on the airplane, as was already noted, the most acceptable engine will be a turbojet, and especially a fan-jet. An STOL airplane must have, as a rule, no fewer than two engines in order to provide flight safety in case one of them fails. With this, as with any short-haul airplane, of the two most important requirements for an aviation engine -- low specific weight and low specific consumption -- the first is the most important for the time being.

4. STOL airplanes brought forth a whole series of new problems connected with flight and technical operation. Specific requirements are outlined for it along the lines of stability, controllability and overall flight safety at low speeds. On one hand, operation of these airplanes is essentially safer due to low values of V_{ldg}. However, on the other hand, low speed flight is connected with the possibility of loosing effectiveness in the normal organs of stability and control. It is thought that they are effective in the absence of the stall phenomenon up to speeds of 90-105 km/h (near the ground). At lower speeds, either normal, increased control organs or special systems (stream gas dynamic rudders, thrust vector control and so forth) must be used. Beginning at some low speeds, the use of special systems becomes unavoidable. In any case, flight on STOL airplanes still requires high qualifications of the flight crew, and the structure and systems of the airplane must possess high reliability. One of the means for increasing reliability in STOL airplanes is full automation of the takeoff and landing stages. /251

The problem of noise is also relatively acute for STOL airplanes, since their usage is planned in the immediate proximity of cities or even inside them. Noise from STOL airplanes is generally less than from normal airplanes, which does not, however, decrease the acuteness of the problem itself. The utilization of takeoff and landing platforms over water and any type of muffler is recommended to decrease noise.

A number of new problems are also being set forth along the lines of technical servicing of airplanes equipped with BLC systems (see p. 230-231).

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5. In creation of STOL airplanes, the problem of weight is complex, since all means for decreasing the takeoff and landing distances of an airplane require great weight expenditures. According to available literary data, the weight of an STOL wing is, as a rule, increased by a minimum of 10-15% as opposed to a normal mechanized wing. The weight of the power unit can increase by 50% (on the Brege 141 airplane, the weight of the synchronized propellers comprises 3% of the G_0, and thepower required by this system is 1.44% of the cruising power). The weight of an STOL airplane's landing gear, if it is calculated for use off dirt airports, is 5-6%. Fig. 6.9 shows, as an example, how the total load ratio of modern STOL airplanes changes with an unchanged takeoff weight depending on the required value for takeoff distance. (To decrease $L_{t/o}$ d, large diameter propellers and extensive wing mechanization are used in the given example.)

23.3. Effectiveness and prospectives of development. From the preceding data, it must follow that modern technical means still do not provide the required effectiveness of STOL's and the advantages of the latter over normal airplanes still have a potential character. Some foreign specialists are announcing that modern science and technology are generally still not ready for creation of such airplanes (just as VTOL and airplanes with laminar flow control). And actually, with all other conditions being equal, the high weight and complexity of STOL airplanes by comparison with normal airplanes also leads to their high cost (Table 6.6).

Direct operational expenses (DOE) in them presently comprise 110-120% of corresponding costs in normal airplanes having a similar purpose. However, deeper economic analysis shows that in modern conditions these airplanes can compete economically with normal ones.

The high route speed and mobility of STOL airplanes allows their more intensive operation, and due to this the dimensions of the required airplane fleet, i.e. the corresponding capital investments, can be decreased.

STOL airplanes also require minimum capital investments in ground constructions. Besides decreasing the dimensions of new airports, this is also connected with the fact that STOL airplanes can be operated, using 95% of all existing airports, while for normal local line airplanes, only 35% of these airports can be used (due to the short runway length). /252

Decreasing delays in airports and simplification of air traffic control (ATC) during introduction of STOL airplanes will also lead to a decrease in airport expenditures. As calculations show, this decrease can compensate for the increase in direct expenses cited above and therefore the total cost per ton kilometer of airplanes of this type will not differ from that for normal airplanes. According to criteria of adjusted costs or the coefficient of /253

profitability, advantages of STOL airplanes, due to the lower capital investments, are even more apparent.

TABLE 6.6. COMPARATIVE COST OF AIRPLANES OF VARIOUS TYPES

	Type of airplane	Relative cost
STOL	Normal airplane	1.0
	With turboprop engines	1.25—1.3
	With turbojet engines (fans in the wing, DLC, reaction flaps)	1.5—1.75
VTOL	With turboprop engines and rotating propellers	1.5—1.75
	With turboprop engines and rotating wing	2.0—2.5
	With turbojet engines	2.0—2.5

The development of STOL airplanes and the increase in their effectiveness in the near future are very interesting. Weight perfection of structures and engines must play the decisive role in this problem, since the weight of these parts of an STOL airplane is especially great in comparison with a normal airplane. According to data from the foreign press, the weight perfection of STOL airplanes will, by 1980, be successfully raised up to the level of normal airplanes. The development of weight characteristics of STOL airplanes can be represented as is shown in Figs. 6.10 and 6.11 and in Table 6.7.

Chapter 24. Vertical Takeoff and Landing (VTOL) Airplanes

24.1. Definition, classification and planning requirements. High-speed airplanes which, due to high thrust-to-weight ratio can vertically take off and also hover stationary in the air have been commonly called VTOL airplanes. The high flight speed is still an organic property of the VTOL airplane, since from conditions of the vertical takeoff, it must possess a high thrust-to-weight ratio. VTOL airplanes go into a class defined by a wider concept -- vertical takeoff and landing aircraft, which also includes various types of helicopters. VTOL airplanes also structurally conjoin with the STOL airplanes just examined, because the capability for a vertical takeoff and landing can usually also be used for shortening takeoff roll and landing roll out. An airplane which can be used as a VTOL and as a STOL is commonly designated a VTOL/STOL airplane. The classification of VTOL airplanes is presented in Fig. 6.12. /254

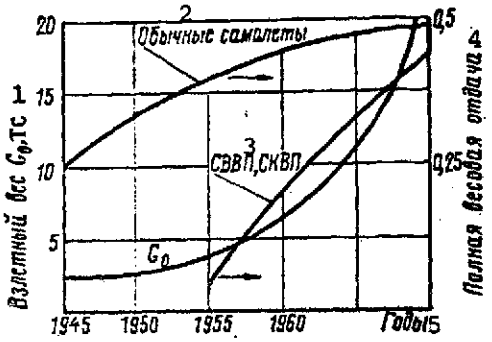

Fig. 6.10. Load ratio of VTOL and STOL airplanes with turboprop engines.

Key: 1. Takeoff weight, G_0, t; 2. Normal airplanes; 3. VTOL, STOL; 4. Total load ratio; 5. Years

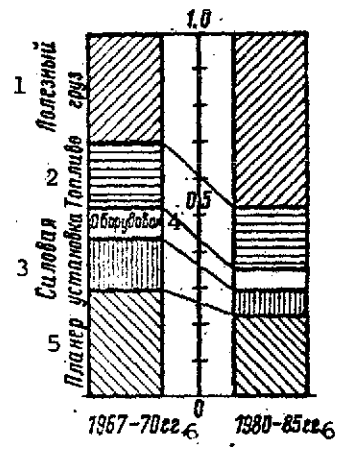

Fig. 6.11. Prognosis of weight perfection of STOL and VTOL airplanes.

Key: 1. Useful load; 2. Fuel; 3. Power unit; 4. Equipment; 5. Airframe; 6. Years

Before examining these airplanes, it is appropriate to remain on helicopters -- the major and for the meantime the only mastered representative of vertical takeoff flying machines. Work on the creation of helicopters began in essence simultaneously with work on airplanes. However, their practical utilization began significantly later. (In the mid 1940's abroad). Takeoff and landing of a helicopter is provided by vertical thrust created by large diameter load-bearing rotors. The thrust for horizontal flight is created through some deflection of the axes of these rotors. The helicopter method for obtaining vertical thrust is the most economic of all those known, since it is based on the movement of a large mass of air at a low velocity (50-60 m/sec, while in a normal turbojet engine this speed is equal to 600-700 km/sec). Due to this, the so-called coefficient of thrust in helicopters reaches a value of 4-5 kg/hp, while in airplanes with a propeller it is 1.5-2 kg/hp (in place) and in turbojet engines it is 0.25 kg/hp. Power units of helicopters at the present time are very different; piston, turboprop, turbojet, liquid-jet, ramjet and pulsejet engines are used for them. For installation of piston and turboprop engines, mechanical drives to the main rotors are used, while turbojet and other engines are used without transmissions. The type of power unit is very important for the characteristics of the helicopter. Installation with a mechanical drive possesses a greater weight, but lower fuel consumption. Conversely, installtions with ramjet or pulsejet engines have a low weight but a high fuel consumption. The load ratio of a helicopter does not differ from that of an airplane. The high weight expenditures on the main rotors, transmission and controls are compensated by the absence of a wing, and the light gear and fuselage.

The basic difference between a helicopter and an airplane consists of the fact that a helicopter possesses significantly lower

TABLE 6.7. PERSPECTIVES OF WEIGHT IMPROVEMENT OF STOL/VTOL AIRPLANES WITH TURBOPROP ENGINES

Weight components	Weight in kg (in parentheses -- in %)		
	1958	1985	
	initial	Unchanged flying and technical data	Unchanged take-off weight
Structure	17300 (31.5)	11600 (28.4)	12920 (23.5)
Power unit	7940 (14.4)	2980 (7.3)	3760 (6.8)
Equipment	4960 (9.0)	3100 (7.6)	3100 (5.6)
Empty weight	30200 (55)	17680 (43.4)	19780 (36)
Useful load	15890 (28.9)	15890 (38.9)	26270 (47.8)
Crew	293	293	293
Oil	107	107	107
Fuel	8460 (15.4)	6880 (16.9)	8460 (15.4)
Takeoff weight	54950	40850	54950

speed and range. The speed of a normal helicopter cannot exceed 250-280 km/h, since the power which can be removed from the main rotors is limited by phenomena of air compressibility and boundary layer separation, and the amount of horizontal component of their thrust is limited by the necessity for providing a high lifting force and by structural considerations. The flight range of a helicopter is limited in connection with its speed: the use of fuel for creating a lift force on a helicopter is extremely less effective than in an airplane due to high induction losses at the main rotor. Naturally, the development of helicopters has always moved only the path of eliminating their basic deficiency, i.e. along the path of increasing speed. Various means have been used to this end, and among them are: improvement of aerodynamic forms; increasing the power-to-weight ratio; decreasing the harmful phenomena of air compressibility and stall on the main rotor blades by selecting sections and using BLC systems; and also using a wing, which unloads the main rotor at high horizontal speeds. The latter direction in the development of helicopters had led to creation of a so-called combined helicopter or rotor-wing, which also has tractor rotors and a wing in addition to the main rotors. The power of the power unit in a combined helicopter, depending on flight configuration, is transmitted either to the main rotors or to the tractor propellers (autogyro configuration), or to both simultaneously. Combined helicopters possess a high speed (400-500 km/h) and long range. However, their load ratio is lower and their construction is more complex and more expensive. /256

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Fig. 6.12. Classification of VTOL aircraft.

Another type of aircraft created on the base of a helicopter but appearing later is the helicopter-airplane (convertoplane). The convertoplane is a helicopter which is transformed into an airplane and back, depending on its flight configuration. Convertoplane layouts are relatively varied. Fig. 6.13 shows the configuration which has become the most widely developed: the same propellers are used for takeoff and landing, and are rotated into the corresponding position depending on configuration. The construction of these aircraft is also highly complex and expensive, however, they can develop speed in excess of 500-600 km/h and have a long flight range. Fig. 6.12 and 6.14 show the original projects for convertoplanes. In a convertoplane (see Fig. 6.12), the main rotor has a unique form with a central triangular part. In the stationary configuration, the propeller is similar to a short wing. In the convertoplane shown in Fig. 6.14, the propeller blades are folded into the turbofan engine pods. The pods, together with the engines, can be rotated, taking either a horizontal or a vertical position. The speed of this convertoplane is over 965 km/h. With these flight data, these convertoplanes can be classified as VTOL airplanes.

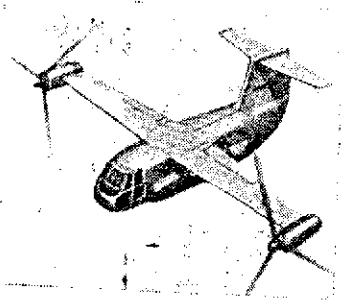

Fig. 6.13. Convertoplane with rotating pods: V = 480 km/h; G_0 = 31.3 t.

As an independent type, VTOL airplanes began to be looked at during the same years as STOL ones, but in connection with the great complexity of this type of airplane, their development was realized at a slower pace. Thus, in the USA, the years 1954-1964 were devoted to investigations as the result of which 18 experimental military airplanes were created, of which only one ("Bell" X-14) /257 remained in operation as a training and test airplane. For our time, great efforts expended in the area of research and development of passenger VTOL airplanes are characteristic. Variations of their civilian utilization are the same as in STOL airplanes and the same requirements are outline for them. However, the possibilities of VTOL are greater than STOL, due to the still less dependence on airports, but the technical difficulties on the way to their realization are also greater. Data from some civilian VTOL airplane projects are presented in Table 6.8.

24.2. Principles and problems of planning. From a technical point of view, the appearance of VTOL airplanes was prepared by development of helicopter construction, the increase in thrust-to-weight ratio of airplanes in connection with the increase in flight speed, the development of jet engines and, first and foremost, the decrease in their specific weight. The role of engines in the problem of creating VTOL airplanes can be judged from the fact that

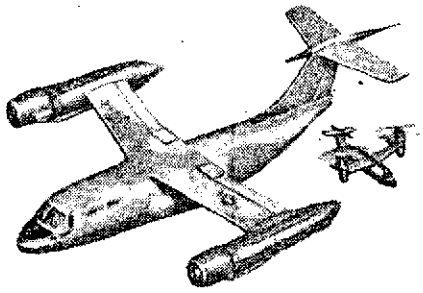

Fig. 6.14. Convertoplane with lifting rotors retractible into rotating jet engine pods; V = 965 km/h.

attempts to construct VTOL airplanes with piston engines terminated in total failure. The relative weight of a power unit with a piston engine on a VTOL airplane reached a value of 50%. Only the use of turboprop engines with a specific weight of engine and propeller on the order of 0.22-0.28 kg/kg of thrust allowed the idea of VTOL airplanes to be first realized. This type of engines still remains one of the most usable for airplanes of the type examined. However, the use of turbojet and turbofan engines is more promising, since it provides higher flight speed. Since the major difficulties in creation of the VTOL airplane are grouped around the power unit, the classification of these airplanes is for the time being most expedient according to engine types and methods of creating vertical thrust with them (see Fig. 6.12). As follows from foreign sources, the most value in recent times is attributed to airplanes with rotating propellers, after which come those with retractible main /259 rotors and, finally, with a rotating wing. Development of VTOL airplanes with lifting engines is for the time being considered the least promising.

Takeoff and landing of the VTOL airplane can be accomplished by two methods: with vertical and horizontal fuselage position. The first method is apparently unusable for civilian aviation. Besides this, complex aerodynamic problems arising during the transfer from the vertical position of the airplane to the horizontal one at low speed force the utilization of a short wing for these airplanes, which makes this configuration advisable only for supersonic airplanes. The complexity of the configuration examined also consists of the fact that the engines and systems of the airplane must maintain their working capacity with the fuselage in any position. The second method is the single acceptable one for civilian airplanes. However, with respect to construction it is more complex.

Like STOL airplanes, VTOL airplanes are for the present time planned primarily with small dimensions. However, the appearance of heavy passenger and transport airplanes is expected in the future.

The load ratio in planning a VTOL airplane is distinguished by its high complexity. It should be noted that a VTOL airplane possesses known prerequisites for decreasing the weight of the wing, empennage, and gear, since takeoff and landing conditions do not impose limitations on any increase in p_0 and do not require powerful wheel brakes. However, the heavy power unit and signi-

TABLE 6.8. DATA OF SOME EXPERIMENTAL VTOL AIRPLANES

Airplane	G_0/T	Engines	v_{cr}, km/h	L km	P_0, kg/m^2	Number of passengers	Means used for vertical takeoff and landing
Dornier Do. 31, FRG	23.5	Turbofan engines 4000 kg x 2, lifting jet engines 250 kg x 10	750	500	420	30–50	Deflection of the cruise engine thrust vector and lifting engines
Fiat G-222 (Italy)	18.8	2 turboprop engines 4 lift turbojet engines	460	3700	270	—	Deflection of stream from propellers with flaps and lifting engines
D-2240 (USA)	7.3	4 turboprop engines with propellers in circular channels	520	900	—	60	Rotation of engines located on two wings
VC-400 (England, FRG)	21.0	Turboprop engines 3745 ehp x 4 D of propellers, 7 m	550	2000	350	60	Rotation of two wings with engines
Dornier Do. 231c (FRG) project	58.5	2 turbofan engines 10800 kg x 2, lifting engines 6000 kg x12	900	800	490	100	As on Do. 31

fuel consumption during takeoff, landing, hovering, stabilization and control require fixed attention on a further increase in weight perfection of this type of airplane, and primarily, on its engines.

Problems of stabilization, controllability and safety of VTOL airplanes at low (essentially zero) speeds are especially complex. Rotation of the thrust vector of the engines, rotation of the exhaust streams, and also special gas-dynamic rudders working both on engine gases and from independent sources are used for stabilization and control. The required safety for takeoff and landing on VTOL airplanes is provided primarily by installation of a large number of engines and automatic synchronization of their operation. VTOL airplanes require a high degree of automation of the airplane's control, to an even greater degree than STOL airplanes.

The problem of noise in VTOL airplanes becomes even more acute than in STOL ones, since as a rule they cause significant noise.

The effect of gases from the lifting turbojet engines on the takeoff and landing area is also a problem. The velocity pressure of these gases is 60 times as great as from a helicopter rotor, and the temperature reaches 400° and higher.

24.3. Effectiveness and development prospectives. The problem of VTOL airplane effectiveness largely comes down to the same problem, examined above as applicable to STOL airplanes (see p. 237). /260

The cost of a VTOL airplane, according to foreign data, is significantly higher than the cost of normal airplanes and often higher than the cost of a STOL airplane (Table 6.6). Direct operational expenses (DOE) in a VTOL airplane are also higher than in normal airplanes, but lower than in helicopters (Fig. 6.15). Together with this, features of the VTOL allow the dimensions of the required fleet to be diminished, and investments in the airport economy are still less with them than in STOL airplanes. Therefore, capital expenditures on a VTOL system prove to be minimal (according to some foreign data, with all other conditions being equal, they will be approximately twice as small as on an STOL system). Therefore, the values of these criteria, as adjusted expenditures or the coefficient of profitability in a VTOL can apparently be better than in an STOL, already at the present time. /261

The foreign press devotes much attention to prospectives in the development of VTOL airplanes. It is noted that the first civilian VTOL's must appear by 1975, and their second, more improved generation by 1985. In the opinion of the chief engineer of the Air Canada aviation company, all flying transport means will be vertical takeoff aircraft without wings or landing gear, i.e. flying fuselages (Fig. 6.16) by the year 2000. Naturally, the

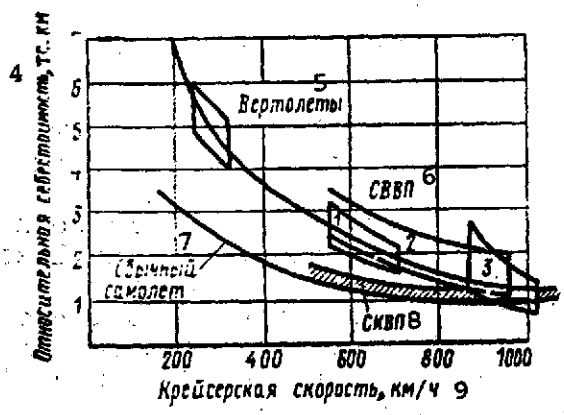

Fig. 6.15. Cost per ton km in different aircraft (flight range 500 km): 1. with rotating wing; 2. with retractable main rotors; 3. with turbofans; 4. relative cost per ton km; 5. helicopters; 6. VTOL; 7. normal airplane; 8. STOL; 9. cruising speed, km/h.

creation of such aircraft will be expedient if a decrease in structural weight through elimination of the wing and gear will exceed the weight connected with installation of additional engines and the increased fuel consumption, i.e. if the weight perfection of structures, equipment and engines is essentially increased.

The means which must be used for this have already been examined above (see also Figs. 6.10, 6.11 and Table 6.8). Possible progress in the area of engine construction can be judged according to the data of Fig. 6.17.

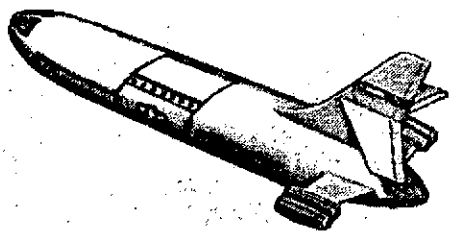

Fig. 6.16. Wingless transport airplane with lifting engines.

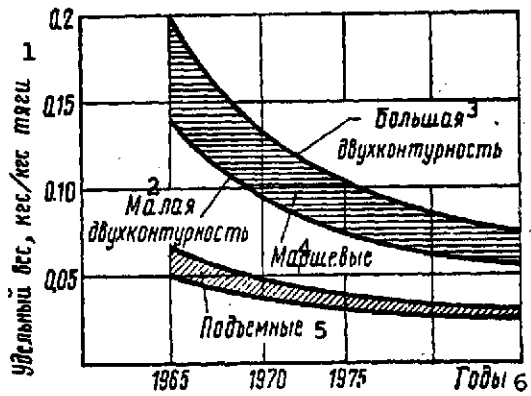

Fig. 6.17. Prognosis of improving weight characteristics of engines.

Key: 1. Specific weight, kg/kg thrust; 2. Low degree of by-pass; 3. High degree of by-pass; 4. Cruising; 5. Lifting; 6. Years

PART 7. PROBLEM QUESTIONS OF FLIGHT RANGE /262

Chapter 25. Ways of Solving the Problem

25.1. Essence of the problem. Increasing the non-stop flight range of passenger airplanes is one of the real problems in modern aviation for the following reasons:

-- Regardless of the fact that flights over long distances (5000-6000 km) comprise a small percentage in the total volume of air movements (see Table 6.2), their volume is constantly increasing. According to foreign data, they have an annual growth rate on the order of 15% on international routes;

-- The distance of long-length routes is constantly increasing, which is explained by the increased industry and population, and by the establishment of new communications between areas and governments;

-- Only aviation provides the essential savings in time on long movements and, especially important, can perform them regardless of distance at approximately the same time, most convenient for the passenger (over 2-3 hours). In this way, while in the area of short distances aviation experiences a significant competition from the side of various ground tranport means, servicing long length routes is the only area of its utilization where its advantages emerge especially clearly. At the same time, the problem of non-stop range is a specific problem of civilian aviation. In other transport means, it becomes either less acute or even totally nonexistent, because firstly, losses in time on stops and refueling are much greater for airplanes than for other transport means and secondly, the basic means for increasing flight range up to the present, because it is more easily within reach, is increasing the relative weight of fuel $\bar{G}_f$. This increase is achieved by increasing the dimensions of the airplane and decreasing the relative weight of the commercial payload. The latter, however, is tied to a significant deterioration in economy of flight. In the area of comparatively short ranges, this deterioration is partially compen- /263
sated by an increase in route speed (through increasing the cruising part of the flight), average aerodynamic quality (through increasing the cruising part and the route effect: airplanes of large dimensions are made aerodynamically more modern). Besides this, due to this route effect, the weight perfection of the airplane increases. However, beginning with some value of range, the decrease in $\bar{G}_{cp}$ necessary to increase $\bar{G}_f$ cannot be compensated by these positive effects and the cost per ton km begins to increase. This explains the presence in airplanes of a definite optimum range, at which the minimum value of cost per ton-km is achieved (p. 206).

If instead of the criterion of cost per ton-km, we turn to more contemporary economic criteria, the problem of economy on long flights stands even more acute before us. It should first of all be

noted that aviation fares are set up similarly to fares of other transport means due to apparent economic considerations, i.e. with an increase in range, they decrease. Secondly, due to a decrease in $\bar{G}_{cp}$ and the relatively high cost of heavy airplanes produced in relatively small quantities, the specific capital investiments (per unit of transport production) increases with an increase in flight range. Therefore, if the increase in airplane speed is itself the source of increasing their economic effectiveness, as was shown above, the increase in flight range is the reason for its reduction. It is therefore not by chance that flight range of airplanes has historically not grown so rapidly as has speed.

At the contemporary level of development of equipment, flight range of no more than 9-10,000 km, achieved on the more modern airplanes, is economically justified. The maximum flight range of these airplanes is 11-12,000 km. Only be replacing the entire commercial payload with fuel can the flight range be brought up to the value of 15-16,000 km, which is the limiting one under modern conditions. It is appropriate to note that the increase in flight range as a whole has a reasonable limit. Thus, for instance, possessing a flight range on the order of 20,000 km, an airplane can reach any point on the surface of the earth without landing. In this way, it is possible to note three characteristic ranges in modern passenger airplanes: the limiting advisable one for geographical conditions (20,000 km); the limiting achievable one from technical conditions (15-16,000 km); and the limiting economically justified one (9-10,000 km).

In ground transport means, this aspect of long trips looks much simpler. Equality of a weight balance in them does not have such acuity as in aviation and therefore an increase in fuel reserve does not effect the value of permissible commercial payload /264 as sharply. Besides this, they have a much lower specific consumption of energy. An increase in their economy is also promoted by the same factors, but again, without essential losses in time, it is possible to vary the amount of commercial payload in them and, in particular, even increase it.

Therefore, considering everything stated above, it is possible to assert that the essence of the problem of civilian airplane range consists primarily of increasing the economic effectiveness of these flights, and consequently, analyzing the means for increasing range, it is necessary to evaluate them first of all from this point of view. These means will be examined in the following chapters.

The basic ways of increasing flight range emanate from analysis of a known range formula and criteria of economic effectiveness of an airplane. This is an increase in flight speed (however, the possibility of this way in subsonic airplanes, as was shown earlier, has practically already been exhausted due to the existence of a corresponding optimum -- see Fig. 6.4); weight perfection of the

airplane; decreasing specific fuel consumption; increasing aerodynamic qualities; optimization of flight trajectories and automation of control of the airplane; refueling in flight (the advisability of using this method for passenger airplanes, however, seems doubtful due to considerations of safety and economy).

25.2. Weight improvement. Increasing the load ratio to increase the fuel reserve has always been one of the most important means for increasing flight range, because this method is not only the most effective but, as a rule, it is also the closest within reach. One cannot lose sight of the fact, and this will be supported by materials presented below, that other methods of increasing flight range always require additional weight expenditures and, consequently, assume the possibility of simultaneously increasing the weight perfection of the construction.

Some possibilities in weight perfection of an airplane are illustrated in Fig. 6.10, 6.11 and 7.1. According to data from the foreign press, by 1980-1985, the relative weight of an empty heavy jet airplane will be successfully reduced by more than half, for instance from 0.40 to 0.17-0.18 due to these measures. The relative fuel reserve with this and the same commercial payload can be increased by 40-45% and range can then be increased by 50%. The possible increase in the cost of the airplane, as follows from the analysis of the "cost of weight" (see p. 212), cannot negatively affect the overall effectiveness of the airplane, which must surely increase. (For more detail see Part 3).

25.3. Decreasing specific fuel consumption. Specific consumption of fuel, as historical experience shows, has the least tendency toward decreasing (Fig. 7.2). /265 This is not difficult to understand, since this characteristic is most of all tied to the physical and chemical properties of the fuel, which in aviation still remains petroleum products. The basic method for decreasing specific consumption in turbojet engines was the increase in their thrust coefficient of efficiency, which, as is known, is expressed with the equation

$$\eta_k = \frac{2}{1 + v_s/v}$$

where v is the flight speed; v_s is the speed of reaction stream.

In a normal turbojet engine, v_s = 600 m/sec, so that with v = 250 m/sec (900 km/h) the thrust coefficient of efficiency equals a total of 0.6. Increasing the quality of air flowing through the engine and thereby decreasing the velocity v_s, it is possible to increase η_k. The first step in this direction was connected to utilization of turbojet engines for driving a propeller, i.e. with the creation of turbojet engines. With this, however, the use of

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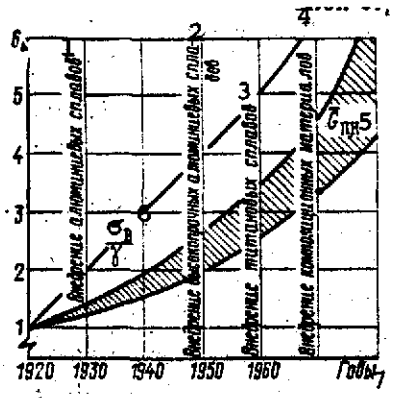

Fig. 7.1. Change in specific strength of materials and total load ratio of airplanes (in relative amounts).

Key: 1. Introduction of aluminum carboys; 2. Introduction of high-strength aluminum alloys; 3. Introduction of titanium alloys; 4. Introduction of composition materials; 5. $\bar{G}_{tl}$; 6. σ_w/γ; 7. Years

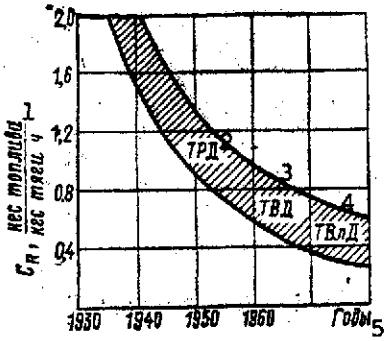

Fig. 7.2. Changes in cruising specific fuel consumption of engines.

Key: 1. C_r (kg fuel)/(kg thrust/h); 2. Turbojet engines; 3. Turboprop engines; 4. Turbofan engines; 5. Years.

propellers limited flight speed (v = 600-750 km/h) and its altitude (H < 8000 m). A further increase in the economy of turboprop engines (by approximately 20-25%) was achieved comparatively recently through the use of heat regenerators. The development of these regenerators was conducted very long ago, but their acceptable weight characteristics were not achieved for a long time. Later success in this direction was connected with creation of turbofan (by-pass) engines. These engines provided flights at high, near-sonic speeds and at high altitudes. The specific consumption of fuel in them was successfully brought down to a value achieved in the best piston engines (see Fig. 7.2). The latest achievement in the development of this type of engine was creation of engines with a high coefficient of by-pass (m = 2-8). Besides minimum fuel consumption, these engines possess one other important feature: they provide better agreement between the characteristics of engine and airplane than normal. The required thrust of an airplane at altitude decreases more rapidly than the available thrust of a normal turbojet or fanjet engine (Fig. 7.3). As the result of this, an engine which is selected, as usual, from conditions of takeoff and acceleration at low altitude to cruise flight must be throttled back, i.e. used with a coefficient of efficiency lower than the maximum. In a turbofan engine with a high coefficient of by-pass (just as in a turbojet engine) the thrust at altitude, due to the great effect of air density on it, drops sharply. Selection of a coefficient of by-pass can bring the engine into full agreement with the airplane, or in other words, provide its usage at all power settings with maximum coefficient of efficiency. Calculations show that the optimum degree of by-pass is m = 8. With this, an additional reduction in fuel

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consumption by approximately 20-25% can be achieved. However, the relatively large frontal areas of these engines do not allow full utilization of their advantages. Fig. 7.4., as an example, shows the comparative characteristics of flight range in heavy transport airplanes with various types of power units.

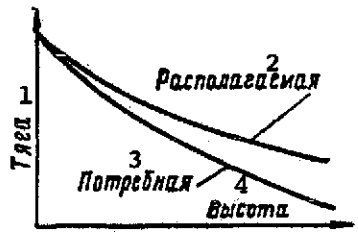

Fig. 7.3. Required and available thrusts of airplanes with jet engines.

Key: 1. Thrust; 2. Available; 3. Required; 4. Altitude

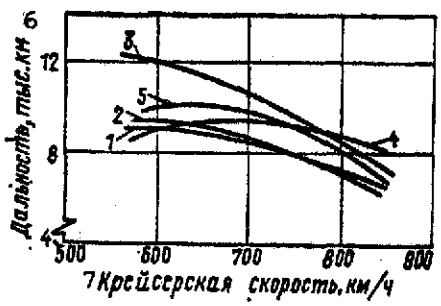

Fig. 7.4. Flight range of airplanes with various types of engines (G_0 = 272 t, G_{cp} = = 59 t): 1. Turboprop engine, 2. Turboprop engine with regenerator (H = 9000 km); 3. Turboprop engine with regenerator (H = opt); 4. Turbofan engine with coefficient of by-pass m = 2; 5. Turbofan engine with high-thrust fan, m = 10; 6. Range, thousand km; 7. Cruising speed, km/h.

Another possible method for increasing engine economy, true, further from practical utilization for the time being, is connected with the use of new high-calory fuels. Basic data on some of these are presented in Table 7.1. Many of these fuels possess high burning stability and high velocity of flame spread, which also allows the dimensions and weight of the engines to be reduced. Their utilization is delayed by such deficiencies as high /267 cost, very high burning temperature, forced usage of ceramic materials, and also the presence in the products of combustion of viscous and hard substances which are harmful for engines.

25.4. Automation and optimization of control processes. Various means of automatic control are used on modern passenger airplanes. Solving the problems of stability, controllability and safety, they also aid in decreasing aerodynamic resistance of the airplane and fuel consumption, enhancing an increase in flight range. Thus, for instance installation of pitch dampers allows an essential decrease in the reserve of longitudinal stability of the airplane, thereby decreasing resistance which arises due to balancing by 3-5%. The use of yaw and roll dampers and automatic skidding device on airplanes with swept wings leads to a similar aerodynamic effect. The use of autopilots and other special devices allowing precise maintenance on a set course, flight altitude and attitude of the airplane in space can lead to a great effect.

For this purpose, the flight trajectory can be optimized according to range [43]. True, the possibilities of such optimization cannot always be utilized under modern conditions due to various operational requirements (altitude separation, noise limitations and so forth).

TABLE 7.1. PROPERTIES OF SOME FUELS

Fuel	Density, g/cm^3	Calorific power, kcal/kg
Kerosene	0.82	10 270
Gasoline	0.68	10 400
Acetylene	0.62	11 500
Pentaborane	0.61	16 200
Diborane	0.45	17 420
Hydrogen	0.07	28 700

The most promising control automation means of an airplane is the use of special on-board computers which allow problems of optimization to be solved during the process of the flight itself, i.e. with consideration for actual conditions. According to some data, the use of digital electronic computer devices in the system for controlling engine power settings decreases fuel consumption by 15%. Such devices, providing optimal engine power settings, also decrease their wear.

25.5. Aerodynamic perfection and laminar flow control. We will examine methods for increasing flight range by improving the aerodynamic characteristics of an airplane. These methods, decreasing the required fuel reserve, as a rule, at the same time require an increase in empty airplane weight. Therefore they, as also always in similar cases, are suitable for use on long-range airplanes, i.e. with a large value for relative fuel weight. As is known, the coefficient of aerodynamic resistance of an airplane can be expressed with the formula /268

$$c_x = c_{xp} + c_{xi} = (c_{xr} + c_{xf} + c_{xw} + c_{xn}) + c_{xi},$$

where c_x is the total coefficient of resistance; c_{xp} is the coefficient of profile resistance; c_{xi} is the coefficient of inductive resistance; c_{xw} is the coefficient of wave resistance; c_{xr} is the coefficient of pressure (form) resistance); c_{xf} is the coefficient of friction resistance; c_{xn} is the coefficient of interference resistance.

The approximate relationship between these components of resistance are shown in Fig. 7.5. At comparatively low subsonic speeds an increase in wing length to decrease the inductive part of the resistance is the most effective. At medium value subsonic speeds the minimum resistance was already achieved at the end of the 1950's through increasing smoothness of the skin, inparting smooth streamlined shapes to the airplane and decreasing its wetted surface, i.e. by means of decreasing profile resistance. The acquisition of high near-sonic speeds was connected first of all with a decrease in wave resistance (development of special wing profiles, usage of "thin" wings of short length, sweep, fuselages with great length and others) and interference resistance (the rule of areas; placement of the engines in the root part of the wing and others).

A new "overcritical" or "inverted" section[1] (Fig. 7.6) was proposed comparatively recently to decrease wave resistance of wings on fast airplanes. Speeds and pressures change more smoothly on the upper, relatively flat surface of such a section than on a normal section. Therefore, the shock wave and stall appear much later. As a result, as wind tests have shown, c_x of this section turns out to be 18-20% lower at high speeds than with normal high-speed sections. To maintain c_y, there is a localized increase in curvature at the trailing portion of the new section, and in some variations a slot is also fixed (BLC is utilized). There are still /269 no results of full-scale testing of the new section.

However, as is visible from Fig. 7.5, friction resistance remains the major reserve up to the present time for decreasing the resistance of an airplane, and the only way to decrease this resistance consists of providing laminar flow of the wing and other parts of the airplane. Fig. 7.7 shows the dependency of the coefficient of profile resistance of the wing on the Re number (determined according to the chord of the wing) and the effect of different methods of laminarization on that resistance. Fig. 7.8 shows the change in the coefficient of profile resistance of airplanes through the years. As is seen from Fig. 7.7, the resistance of a laminar flow wing is 5-6 times smaller than under normal flow conditions.

The first steps in the direction of airplane flow laminarization were taken long ago. They consisted of providing smoothness and evenness of the skin (concealed rivets, filling, painting, polishing, the method of assembly "from the skin" and so forth). Among the first attempts of this type are also included such means as NASA rings, TsAGI[2] rings, Townend rings and so forth, which were used to decrease engine installation resistance. These devices, by means of blowing air through a slot in the engine cowling, provided separation of the sluggish, retarded boundary

[1] Aviation Week 24, 25 (July 1967).
[2] TsAGI -- Central Aerohydrodynamic Institute

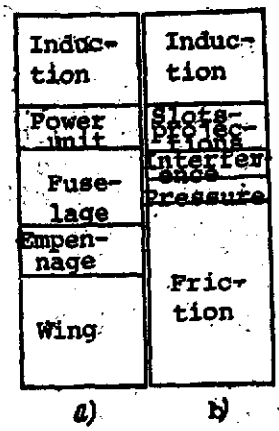

Fig. 7.5. Components of aerodynamic resistance of a long-range transport airplane (M_{cr} = 0.8): a - by parts of the airplane; b - by types of resistance.

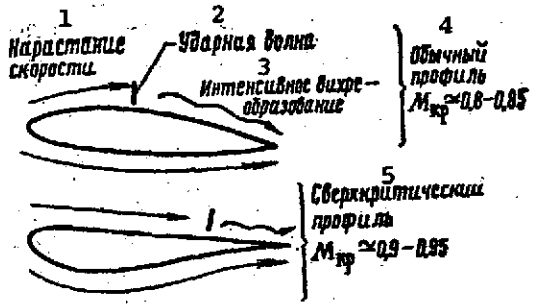

Fig. 7.6. Whitecomb's overcritical section.

Key: 1. Increase in speed; 2. Shock wave; 3. Intensive vortex formation; 4. Normal section $M_{cr} \sim 0.8$-0.85; 5. Overcritical section $M_{cr} \sim 0.9$-0.95.

layer and thereby decreased c_x of the cowling by 50-40%. At the beginning of the Second World War, so-called laminar sections were proposed, which were calculated to maintain laminar flow on a significant portion of the wing chord. Since acceleration of the flow and negative pressure gradients take place immediately before the point of maximum section thickness h_{max}, to increase the zone of laminar flow, the position of h_{max} in these sections was shifted closer to the trailing edge up to 50-60% of the chord. With proper polishing of the wing surface, the critical Re numbers in these sections was 10-15 times greater than in normal ones. Practice showed, however, that due to unevenness and roughness on the sking and various external disturbances in the flow, laminar streamlining of these sections proved to be unstable. Besides this, they possess lower values of $c_{y\ max}$, which necessitates utilization of very extensive wing mechanization. /270

Nevertheless, these sections have not lost their value up to the present time and are used in airplane building practice. Living nature provides many examples of successful solution of the laminarization problem. The development of a resilient skin like the leather covering of dolphins, capable of damping arising vortices is very interesting in connection with this [36]. Other suggestions of a similar type are also known, for instance, covering the wing with a sheath with fiber nap (borrowed from the birds) or a system of wire fibers located along the flow.

However, the most attention is now being paid to laminarization of the airplane's flow-past by means of forced suction of the boundary layer from its surface. Besides the inherent effect of laminarization on the value of c_x, elimination of the stall phenomenon will also be affected with this. The system of boundary layer suction to decrease c_x of an airplane has been named laminar flow control (LFC). It is usable both for subsonic and for

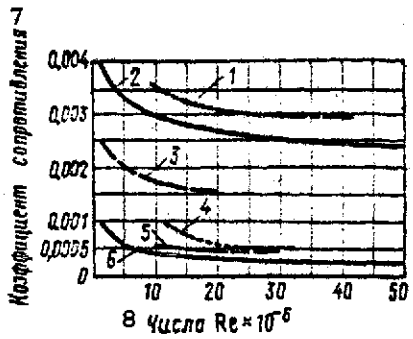

Fig. 7.7. Decreasing profile drag with LFC: 1. Typical series wing; 2. Smooth, flat turbulent plate; 3. Polished wing; 4. Wing of f-94 airplane with BLC; 5. Blow-off of swept wing with LFC; 6. Flat laminar plate; 7. Coefficient of resistance; 8. Re number x 10^{-6}.

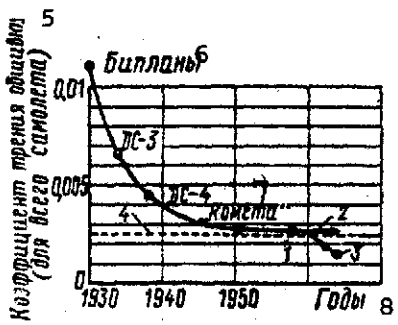

Fig. 7.8. Tendency of decreasing the coefficient of friction: 1. Typical jet passenger airplane with turbulent boundary layer; 2. Without use of LFC; 3. With use of LFC; 4. Lower limit with turbulent streamlining; 5. Coefficient of friction for the skin (for the entire airplane); 6. Biplanes; 7. "Comet;" 8. Years.

as the result of replacing piston construction of the LFC system; supersonic airplanes. The theoretic advisability of creating an LFC system on an airplane emanates from the fact that the energy required to suck off the boundary layer proves to be significantly less than that which is needed to overcome drag caused by this layer. This is explained by the fact that the mass of the boundary layer, due to its minute thickness, is very small and therefore the required speed of suction turns out to be many times smaller than flight speed. The idea of LFC is similar to the idea of lubricating sliding parts: theuse of lubricant is significantly more economic than overcoming the force of resistance in its absence. /271

Suction of the boundary layer to decrease drag was first proposed by Prandtl in 1904 and was then realized experimentally. Approximately 20 years later than that, a wing with boundary layer suction was tested, and at the end of the 1930's a large number of tests and investigations devoted to this problem were already being conducted. In particular, in the USSR, the first tests of this type were conducted in 1933-1935 by engineers N. A. Zaks and P. P. Krasil'shchikov under the initiative of TsAGI.
However, practically important results with the LFC system were obtained comparatively recently on the basis of such scientific and technical achievements of recent times as:

-- Creation of turbojet engines, which eliminated the disturbing effect of the propellers on the wing and allowed utilization of the weight reserve formed engines with turbojet ones on

-- Progress in the technology and methods of construction, based on experience in creation of the LFC system and allowing obtainment of suction panels which were light and had good surfaces;

-- Development of theories and methods for calculating the boundary layer.

Many factors affect the conversion of a laminar boundary layer to a turbulent one, primarily: boundary layer separation, unevenness and roughness of the surface of the body, turbulence of the onrushing stream, caused by some external reasons, acoustical phenomena, structural vibrations, pulsation of the stream in boundary layer suction slots (if a BLC system is used), with high M numbers -- jumps in density, increased temperature, etc.

It has become common to consider the Re number as the basic criterion of laminar flow stability. It is then established with tests that with Re_δ greater than 3000-10,000 (here σ is the thickness of the boundary layer), the laminar flow becomes unstable and the reasons to convert it into a turbulent one are relatively insignificant. Laminarization of the wing and empennage and even the pods is in the general case easier than that of the fuselage, due to the presence of many projections, hatches, doors, windows and so forth on it. Laminarization of a straight wing is simpler than that of a swept one. While the flow-past of a straight wing can be seen as flat (bimeasure) and the use of one criterion of stability, the Re_σ number mentioned above is sufficient for its analysis, the flow-past of a swept wing is spatial (trimeasure), since its boundary layer, besides the basic flow along the chord of the wing in the direction of the normal field of pressure gradients, also has a second flow along the span of the wing causing the presence of corresponding pressure gradients on the swept wing. The second flow changes the fields of velocity and pressure of the main flow, creating points of flexion in them, in which pressure gradients reach very high values (Fig. 7.9), which causes extreme instability of the boundary layer on a swept wing. This instability is also aggravated by the fact that the fuselage boundary layer flows off onto the leading edge of the wing at point A (see Fig. 7.9). Moving along it, it disturbs the boundary layer of the entire wing. In this way, boundary layer stability in a swept wing must be evaluated according to three criteria: main flow stability, secondary flow stability and stability on the leading edge of the wing. Experimental values for critical Re numbers have been obtained for each type of flow. /272

The most significant volume of full-scale testing of the LFC system was performed on the X-21A airplane (Fig. 7.10) with a laminarized wing, built on the base of a Douglas B-66 airplane. The Re number during tests was located within the range of Re = $= 20 \cdot 10^6 - 40 \cdot 10^6$ and C_{xo} was reduced from 0.022 to 0.179. The lift-to-drag ratio was increased by 25% (with full laminarization of the entire airplane, according to calculations the lift-to-drag

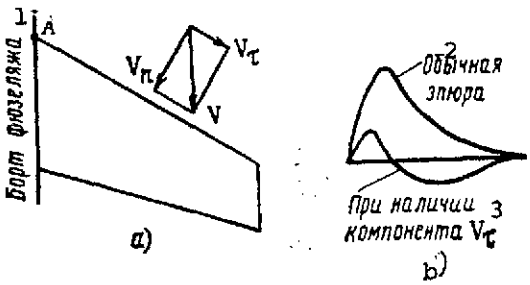

Fig. 7.9. Velocity components for flow-past of a swept wing (a) and pressure curve along the chord (b).

Key: 1. Side of fuselage; 2. Normal curve; 3. In the presence of component V_τ

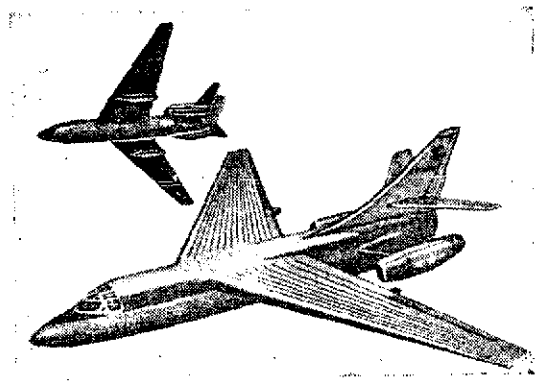

Fig. 7.10. X-21 airplane with laminarized wing.

ratio would have been increased by 32%). Testing of this airplane supported the correctness of the calculations and proved the practical possibility of laminarization of a swept wing. Power units with engines working on the boundary layer can be considered among possible perspectives for further development of the LFC system. The air intake of such a power unit might consist of a number of slots located along the upper and lower surfaces of the wing in the area of the trailing edge. The retarded air of the boundary layer must be sucked into these slots and then ejected through similar slots on the trailing edge of the wing. The effective laminarization of flow-past will thereby be combined with the immediate utilization of the energy of suction for creation of thrust. For the time being, similar systems are not very effective and are /273 complex, since air from the boundary layer arrives at low pressure and with an uneven velocity field. However, the perspectives of this method, which requires, true, many totally new solutions, are very promising in the opinion of its author.

Chapter 26. Airplanes with LFC

26.1. Layout and parameters of the airplane. The immediate results of using an LFC system on an airplane are: a significant decrease in drag and a corresponding increase in the aerodynamic quality of the airplane, an essential change in the weight structure of the airplane, and the appearance of new requirements for the power unit. These results have a decisive effect on the layout, arrangement and basic parameters of the airplane. Therefore, we will stay on them in detail.

Examining the drag of a laminarized airplane, it should be first of all kept in mind that for functioning of the LFC system, expenditures in power are required, which for the sake of calculation convenience are commonly expressed through additional equivalent aerodynamic drag:

$$\Delta C_{x\ LFC} = \frac{\Delta R}{qS}$$

where ΔR is the loss in engine thrust for pump drive; q is the dynamic pressure of flight; S is the wing area.

In the next presentation, it will be asserted everywhere that /274 the value of $\Delta C_{x\ LFC}$ sometimes called the "equivalent drag of the pumps," is included in C_x of the airplane. According to calculated data, it comprises an average of 20% of the actual drag of a laminarized airplane.

A decrease in drag and an increase in the lift-to-weight ratio depends most of all on the scale of the airplane's laminarization. As is seen from Fig. 7.5, the specific weight of friction drag in the total drag of the airplane at M = 0.8-0.85 is 40-50%. Laminarization decreases friction resistance by 5-6 times (see Fig. 7.7) as the result of which the total drag of a laminarized airplane can comprise 40-50% of the drag of the initial one, i.e. be decreased by 2.0-2.5 times. However, laminarization of the entire airplane, as was already mentioned, is not very probable with contemporary technical means. For the time being, laminarization of the wing or wing and fuselage is most possible, and to a lesser degree, laminarization of the pods and fuselage. Laminarization of a passenger airplane fuselage is difficult, in particular due to the complexity of locating sufficiently large pipelines within it. FIg. 7.11 shows the increase in lift-to-drag ratio of a near-sonic airplane in dependence on the scope of laminarization, which is evaluated with the relationship of the area of laminarized surface of the airplane S_{LFC} to the area of its total wetted surface S_{wet}.

It is evident that laminarization of the wing will be most effective for an airplane of the "flying wing" type. It will be less effective for passenger and transport airplanes with thick fuselages (the relationship S_{LFC}/S_{wet} = 0.4-0.5). The effect from laminarization of the wing, empennage and pods in a passenger airplane will increase with an increase in its takeoff weight, since with this the relative dimensions of the fuselage will be decreased (Fig. 7.12).

The effectiveness of laminarization essentially depends on the /275 basic geometric dimensions of the airplane. The fact of the matter is that with a decrease in the profile drag of an airplane through the use of the LFC system, the value of inductive drag begins to increase relatively. It is also known that the value K_{max} is always achieved with equality of $C_{xp} = C_{xi}$. Therefore, decreasing C_{xp}, to obtain the maximum effect, C_{xi} must also be decreased. This can be achieved in two ways: by increasing wing length λ, which cannot always be justified since it is connected with a significant increase in the weight of the wing, and increasing

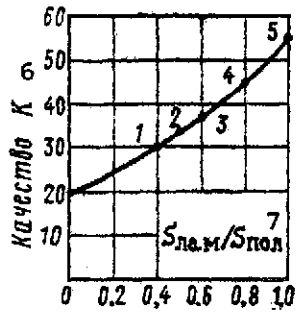

Fig. 7.11. Dependency of lift-to-drag ratio on the degree of laminarization: 1. wing; 2. wing and empennage; 3. wing, empennage and pods; 4. all surfaces except half the fuselage; 5. all surfaces (airplane optimized for LFC); 6. lift-to-drag ratio K; 7. S_{lam}/S_{tot}.

wing area S, i.e. decreasing specific wing loading. The second way is more effective, since it decreases the required value of C_y and is connected with a smaller increase in wing weight. The use of this method is preferred and is seen more frequently. Fig. 7.13 shows the diagram for selection of the optimum wing area of a normal airplane and for an airplane with LFC, from which it follows that in the latter, optimal wing area must be greater (by 15-30% according to data of various calculations). Effectiveness of the laminarization of an airplane is also affected, true, to a lesser degree, by the sweep and relative thickness of the wing, and also by flight altitude, M number and others. Calculations show that laminarization of an airplane, in combination with optimization of its parameters is approximately twice as effective as simple laminarization. Fig. 7.14 shows, as an example, polars of a long-range transport airplane with an LFC system and without it.

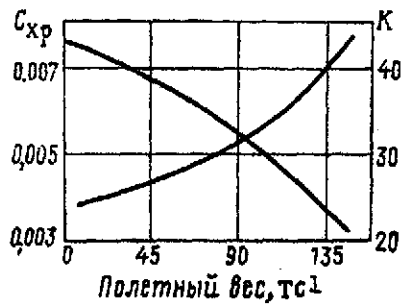

Fig. 7.12. Equivalent values of C_{xp} and K (all surfaces except the fuselage laminarized).

Key: 1. Flight weight, t

Installation of an LFC on an airplane with maintenance of flight data must lead to the following changes in its weight structure: empty airplane weight is increased due to the larger wing area and installation of the LFC system; the required fuel reserve is decreased; the required thrust-to-weight ratio and, consequently, the weight of the engines is decreased. (Takeoff and landing characteristics in this case must be provided through a lower specific wing loading). /276

In the first approximation, the change in weight of the wing and engines can be considered mutually compensating, since their relative weights approximately coincide in modern airplanes (each comprises on the average of 10% of takeoff weight). The increase in empty airplane weight due to the LFC system is evaluated at approximately 3.5% of takeoff weight according to data on hand (Fig. 7.15). A decrease in required fuel weight can be taken as proportional to the increase in lift-to-drag ratio in the first approximation.

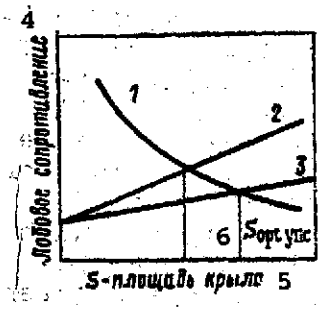

Fig. 7.13. Determination of optimal wing area: 1. inductive drag; 2. friction drag (normal airplane); 3. friction drag (airplane with LFC); 4. frontal resistance; 5. S-wing area; 6. S_{opt} LFC

The aerodynamic and weight results of laminarization of an airplane can be realized in different ways. The following variations (Table 7.2) arouse theoretic interest. The variation with an increase in G_0 turns out to be possible because due to the increase in wing area, considerable unused spaces appear in it. Filling these with fuel will have little effect on the wing, since fuel increases its unloading and proves to be advantageous from the point of view of weight for the purpose of this solution. A detailed examination of the possibilities of the variations presented above is difficult since they require concrete analysis. Therefore, we will limit ourselves to the following example: an LFC system used on the wing and empennage of a heavy transport airplane (G_0 = 136 t), calculated for 130 passengers, under conditions of optimization of dimensions allow the number of passengers to be increased up to 240, i.e. by 84% (with the same takeoff weight) or takeoff weight to be decreased by 20-25% with the same value for G_{cp}, or flight range to be increased by 50-60% (G_{cp} = const). /277

For airplanes with LFC, it is most advisable to use jet engines, and especially those with a high coefficient of by-pass. The capability of the latter to be compatible with an airplane has already been spoken of above. An airplane with LFC is characterized by the fact that its required cruising thrust, due to engagement of the LFC system in flight, drops very sharply and proves to be not only less than with a normal airplane but, more important, much less than takeoff thrust. The use of propeller engines on an airplane with LFC is eliminated due to their turbulent effect on the wing.

Power for driving the suction pumps in an airplane with LFC can be obtained by three methods: from the main engine; from autonomic engines; the main engines can be used directly as pumps. The first method is theoretically the best, since diversion of power from the main engines decreases the velocity of gas outflow, and the exhaust of the pumping system itself creates some thrust. As teh result of this, the flight coefficient of efficiency of the power unit is increased by approximately 5-10%. The main engine-pump system can be seen in this case as an engine with an increased coefficient of by-pass. The second method, which lags behind the first in economy, is better than the first in arrangement and operational indices: the pumping system channels are shorter and lighter, and provision of operation of the LFC system independent of engine power settings is simpler. The third method lags behind both the /278

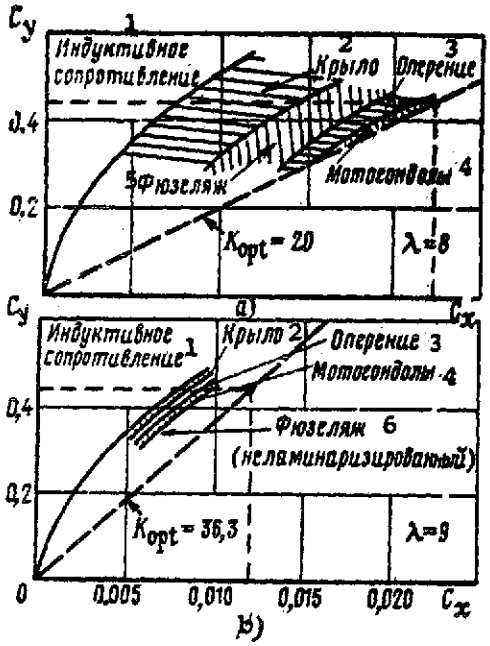

Fig. 7.14. Polar and drag components of a long-range transport airplane before (a) and after (b) laminarization, M = 0.8.

Key: 1. Inductive drag; 2. Wing; 3. Empennage; 4. Engine pods; 5. Fuselage; 6. Fuselage (unlaminarized)

the preceding ones, since collection of air from the boundary layer is connected with high losses in pressure and will lead to a sharp decrease in the thermal coefficient of efficiency of the engines. However, as was shown above, this method is seen as one of the perspectives for development of future engines (see p. 258).

The use of an LFC system places an essential impression on the layout and arrangement of the airplane. Since this system is calculated for a "clean wing," the engines must obviously be placed in the tail portion of the fuselage. The high-wing configuration, with which it is easier to avoid dirt falling onto the surfaces of the wings, which are equipped with suction devices is preferred, although from the point of view of minimum interference, as is known, other configurations are more feasible. In the future, obviously, special shapes for such airplanes will be developed with very even and smooth outlines without projecting parts. Since the resistances of induction and form will acquire ever greater meaning as laminarization is developed, airplanes with LFC will have to have wings and fuselages with great lengths. It is possible that utilization of LFC systems on airplanes will serve as an emphasis for the widespread development of the flying wing configuration, which for a long period of time has not yet moved outside the category of exotic ones. It is also curious to note that the conception of an LFC airplane is totally opposed to the conception of VTOL airplanes, since the development of the latter, as was already noted, will logically lead to wingless airplanes of the flying fuselage type.

26.2. Peculiarities in construction and operation. The construction of an LFC system is composed of the following elements: an external surface of laminarizing components, finished in a manner corresponding to creation of the required penetrability; suction pumps with a drive system; channels connecting the pumps with the external surface of the components and; adjusting devices and equipment.

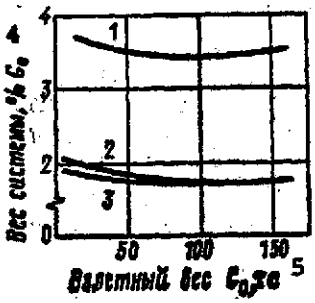

Fig. 7.15. Weight of an LFC system (entire surface except fuselage laminarized): 1. total weight; 2. pumping system; 3. increase in surface weight (according to data of [86]); 4. weight of system, % G_0; 5. Takeoff weight, G_0, t

Empty airplane weight with installation of an LFC system will increase by approximately 3.5%, with which the increase in weight of surfaces is evaluated at 2-4 kg/m^2, and the weight of the remaining elements of the system, as related to the same surface, is located within limits of 6-7 kg/m^2 (see Fig. 7.15). /279

The finishing of component surfaces can be accomplished by various methods; by means of installing a porous skin, skin with slots and a perforated skin. The skin type determine the character of suction, which can be either spread along the surface (with porous or evenly perforated skin) or discrete (with the skin slotted or having perforations like slots). Distributed suction is theoretically more perfect, since its quality does not depend on the character of the pressure field on the suction surface which, for instance, in swept wings can be very complex due to the presence of secondary boundary layer flows on them. However, porous constructions are as a rule, the heaviest, most expensive and least convenient in operation. They are easily contaminated and damaged. Besides this, throttling of suction along the chord or span of the wing, which is necessary due to unevenness of the pressure field is made more difficult with a porous skin. There are also many difficulties in connection with the use of a perforated skin. In particular, it has turned out that small holes (0.2-0.25 mm in diameter) are themselves a source of boundary layer turbulence. At the present time, it is thought that the use of slots is most constructive. The use of slotted suction on a straight wing is not connected with particular difficulties. A

TABLE 7.2. VARIATIONS IN USING RESULTS OF LAMINARIZATION

Variations	a_0	a_{cp}	L
I	const	Increase	const
II	Increase	const	const
III	const	const	Increase
IV	Increase	const	Increase

swept wing can be designed in such a way so as to provide the straightest possible isobars in the boundary layer and to make them as close as possible to parallel with the longitudinal structural elements of the wing, which will determine the direction of the slots.

The average distance between slots has been taken to be approximately 50 mm. The slots are placed more frequently in the leading and trailing portions of the wing section. In the middle they are more sparse. This is explained by the fact that in the leading and trailing portions of the wing, the external pressure has the highest value and the greatest bleed-off must be provided there. Adjustment of suction bleed-off both along the chord and along the span is also provided by throttling holes in the suction panels. It is advisable to use several pumps (a minimum of two -- high and low pressure) or a multistage pump forming mainstreams of high and low pressure respectively to decrease loss in throttling and decrease weight in the system.

A requisite condition for designing laminarized surfaces of an airplane with LFC is imparting maximum evenness and smoothness to them, so as to eliminate extra turbulence in the flow. An important requirement for designing a swept wing calculated for the use of an LFC system is provision for small localized values of the M numbers (less than 1.04). Otherwise, powerful variations in density might introduce indeterminateness into the distribution of /280
pressure on the wing. Special suction with slots located perpendicular to the leading edge of the wing are used to combat turbulence along the edge.

The channel system for LFC is formed of channels located in the skin panels, collector channels and main channels (Fig. 7.16). The velocity of air in the channels must be very low and constant for stability in operation of the system, and the channel sections must consequently be relatively large. This requirement creates definite structural and arrangement difficulties and forces the channels to be combined as much as possible with the main load-bearing structures of the airplane.

The main calculation parameter in the suction system is the consumption of air, which is defined, for instance for a wing according to the formula

$$Q = C_q v S_{LFC}$$

where Q is the volume consumption of air per unit of time; v is the flight speed; S_{LFC} is the area of a wing serviced by the LFC system; C_q is the coefficient of consumption.

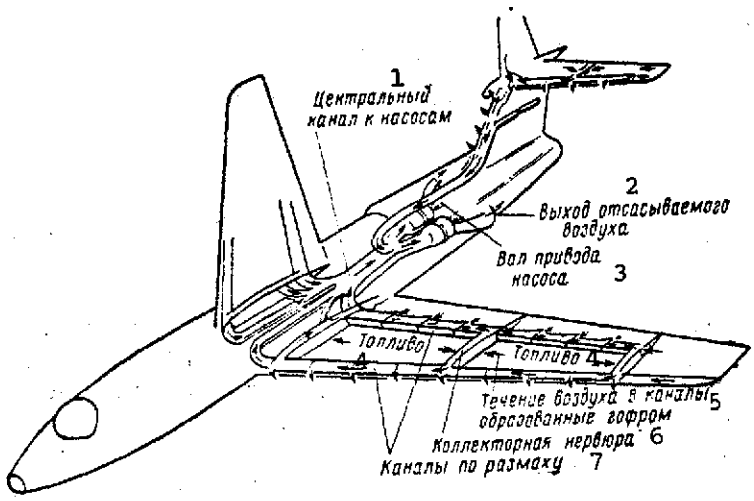

Fig. 7.16. Diagram of LFC system airpipes on the HP.113 airplane.

Key: 1. Central channel with pump; 2. Sucked air outlet; 3. Drive pump shaft; 4. Fuel; 5. Flow of air in channels formed of corrugated metal sheet; 6. Collector rib; 7. Channels along span

A typical value for the coefficient of consumption for straight wings is C_q = 0.0003-0.0004 and for swept wings, C_q = 0.0005-0.0007. Pumping velocity in places where pressure gradients are low is approximately equal to v_{pu} = 0.0001 v. In places with high pressure gradients (the leading edge of a swept wing) v_{pu} = 0.001 v.

Experience in flight operation of the X-21A airplane, which is /281 equipped with an LFC system, according to data from the foreign press, proved the practical reality of creation of such airplanes. Nevertheless, the problem of possible failures of an LFC system on a passenger airplane deserves much attention. A relative seriously and lengthy failure might affect the entire flight plan and cause a premature landing. The creation of reserve fuel supplies on an airplane in foresight of similar cases is advisable.

Technical servicing of an airplane with LFC has its specifics, although in complexity, it does not essentially differ from a normal system. According to data published in the foreign press, labor consumption of servicing an airplane with LFC is approximately 20-25% greater than on a normal airplane, and the cost is 9-10% greater. The basic requirements in technical servicing of an airplane with LFC come down to the necessity for maintaining cleanliness, evenness and smoothness of the suction surfaces, preventing their contamination and damage, and control and adjustment operations

on the pumping system. A porous skin is contaminated very easily. A slotted skin can be contaminated primarily when parked. In order to avoid this, covers should be used or the slots should be blown out with air using a stationary installation. Contamination of surfaces by insects during flight does not generally cause any serious consequences, since insects rapidly dehydrate, freeze and are blown off in the airstream. Besides this, it is possible to use special means against such contamination such as covering surfaces with lacquers containing teflon, chostaflon and other substances which repel protein substances; covering the leading egdes of the wings before takeoff with light sticky films which after attainment of a definite flight altitude are cut away with special devices and thrown off by the airstream and; cleaning the wing during flight with spraying of water or soap solutions, for which special nozzles are installed in the leading edges of the wing. According to tests, wing cleaning time is 20-30 sec.

26.3. Effectiveness and perspectives of development. The planning, production and technical servicing of airplanes with LFC unavoidably requires greater specific expenditures (per unit of empty airplane weight) than with a normal airplane. In particular, an increase in production expenditures is explained by the more complex construction and technology of manufacturing suction panels, which is tied to the increased requirements for the quality of their external surface (evenness and smoothness). The increase in expenditures on technical servicing is connected with the same additional requirements which were spoken off above. As a whole, the increase in specific expenditures on planning, production and technical servicing of an airplane with LFC by comparison with a normal airplane is, because of various sources, evaluated as approximately 10-20%. This increase in expenditures /282 is extremely small if it is compared with the increase in the airplane's productivity which the LFC system provides. Therefore, indices of cost and profitability of operation of this airplane prove to be essentially better than in a normal one, even if it is admitted that the cost evaluations presented above are reduced. A change in these indices depends on the variation of LFC effect realization. Thus, for instance, for the airplane examined as an example above, we get:

-- With an increase in commercial payload weight and conditions (G_0, L) = const, DOE is reduced approximately inversely proportional to the increase in commercial payload, i.e. by $1 - 1/1.84 = 46\%$,

-- With an increase in flight range and conditions of (G_0, G_{cp}) = const, DOE is reduced by approximately 13-15%;

-- The utilization of the LFC effect to decrease takeoff weight, i.e. with conditions (G_{cp}, L) = const, will also lead to a decrease in DOE by approximately 13-15%.

Simple calculations show that an essential increase in the coefficient of profitability of the airplane will be provided in all the variations presented above. In this way, a significantly higher effectiveness of the airplane with LFC by comparison with normal airplanes, even with contemporary technical possibilities is demonstrated without work. Consequently, the center of gravity of this problem lies first of all in solution of basic theoretical, construction, production and engineering problems. It must be noted that the LFC system is also extremely promising for supersonic airplanes, where besides its main effect, it significantly decreases the external temperature of the airplane skin and the noise level. According to relatively unanimous forecasts published in the foreign press, airplanes with LFC doubtless have a great future.

Chapter 27. Essence of the Problem

27.1. Basic concepts and definitions [15, 26]. The modern stage of aviation development is characterized by extreme aggravation of the problem of reliability, the essence of which consists of the fact that the development of equipment requires a constant increase in the reliability of products and, at the same time, creates grounds for its decline. The reliability problem is not new, although it has only now achieved such a condition that, according to the expression formed by Academician A. I. Berg, it has become problem number one.

The definition of reliability is given in GOST [All-Union State Standard] 13377-67 "Reliability in Equipment." According to this document reliability should be understood to mean the property of the product (machine, construction, instrument, etc.) to perform set functions, maintaining its operational indices under set conditions within set limits over the course of the required period of time or the required run. The concept of "set conditions" includes characteristics of the medium in which the product works (temperature, moisture, working rate and character of servicing). Run is understood to mean the volume of work, measured in amounts characteristic for the product (units of work, running time, flight, etc.). The reliability of a product is characterized by a number of indices, namely its "dependability," repairability, longevity, preservation and others. The problem of reliability arose earliest of all in the electronic radio equipment industry. Therefore, the corresponding terminology bears traces of the specifics of this branch.

Dependability is understood to mean the capability of the product to work absolutely reliably over the course of some time. For the quantitative evaluation of this concept, the following indices are presented:

-- Probable number of failures per 1 h of work λ,

-- Average time of failure-free operation $T = 1/\lambda$,

-- Probability of failure-free work of the device over time t /284

$$P(t) = e^{-\lambda t},$$

-- Probability of failure over working time $P(Q) = 1 - e^{-\lambda t}$.

The indices defined by these formulas sufficiently characterize only unrestorable products, i.e. products for which repair during

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the process of their operation is not provided. For restorable (repairable) products, the following additional indices are introduced:

-- Average duration of repairs τ,

-- Coefficient of preparedness, which evaluates the time the product remains in the unservicable condition: $K_p = T/(T + \tau)$.

Repairability evaluates the complexity, labor consumption and cost of repair and servicing the product, including adjustment operations. Longevity is a concept having meaning primarily for repaired products and designating for them none other than reliability over the course of an extended period of time with consideration for repairs. The following are seen as measurements of longevity: the service life of the product, i.e. thetotal calender duration of its operation before it reaches a definite limiting condition (destruction, danger of further operation, economic feasibility of further repairs and so forth) or the technical resource, i.e. total time the product is in a working condition during the entire time of operation.

Therefore, a single criterion of product reliability, which is so necessary for evaluation of practical solutions, does not yet exist. The prediction of its character, if it is created, is difficult. However, it is possible to propose that this must be an economic criterion. It might be, for instance, an index considering the effect of the reliability of the product on the profitability of its operation.

Evaluation of the reliability of an airplane is especially problematic. On one hand, it is difficult to coincide the reliability of its parts and systems with the reliability of the airplane as a whole. On the other, the reliability of an airplane is tightly interwoven with the concept of safety, and airplane accidents are as a rule connected with great material losses.

27.2. Reasons for appearance of the problem. We will dwell on the reasons causing a sharp increase in the role of reliability under contemporary conditions. These reasons are: the increase in structural complexity of machinery, increasing complexity in conditions and higher operating rates; improvement of construction and increased effectiveness of machinery; widespread development of cooperation during creation of machinery and; the historically determined lag of the reliability problem behind other problems.

The unusual and ever-increasing structural complexity of /285
modern equipment will lead, as calculations showed, under otherwise equal conditions, to a catastrophic drop in reliability. In particular, the complexity of aviation equipment is expressed in an increase in weight and dimensions of airplanes, their equipment

fitting, complexity of the structure of the airplane, systems, components and so forth. We will present a simple example. On the B-17 and B-29 airplane, built in the USA in 1940-1945, electronic equipment consisting of 1000-2000 parts was used, while on the B-58 airplane (1960), their number increased up to 95,000. The drop in product reliability as a function of its complexity can be illustrated by the following example. Let the product consist of n elements. We designate $P_i(t)$ as the probability of failure-free operation of each of these over time t. For simplicity, we assume that the failure of any of them does not depend on failures of others and that the failure of any element also means the failure of the product as a whole. Then, according to the theorem of multiplication of probabilities of independent events, the probability for failure-free operation of the product is expressed by the formula

$$P_0(t)=\prod_{i=1}^{n} P_i(t).$$

And if all elements of the product are identical, then

$$P_0(t) = [P(t)]^n.$$

The results of calculations according to this formula are presented in Fig. 8.1. They show that the reliability of a system, if special measures are not taken, will be less than the reliability of the unreliable element itself.

The second reason for a drop in reliability of temporary equipment consists of complexity of conditions and increased operating rates. We have in mind the increase inspeeds, loads, pressures, temperatures, increased requirements for precision in manufacture and operation of the equipment and so forth. Thus, for instance, in aviation the increase in flight speeds led to an increase in the number of cycles of sign-changing loads on the airframe and the problem of fatigue, and then acoustic strength emerged.

The third reason is connected with improvement of contemporary equipment for the purpose of increasing its effectiveness. This relates to the struggle for reduction of weight and dimensions of /286
machines, their cost and so forth. A decrease in the relative weight of the airframe, the decrease in specific weight of engines, and the decrease in dimensions and weight of radio electronic gear can serve as clear examples of this improvement. Thus, the relative weight of the airframe over the time of aviation's existence has decreased from $\bar{G}_{af}$ = 0.4-0.5 to $\bar{G}_{af}$ = 0.2. The specific weight of internal combustion piston engines in 1900 was 250 kg/hp, and in

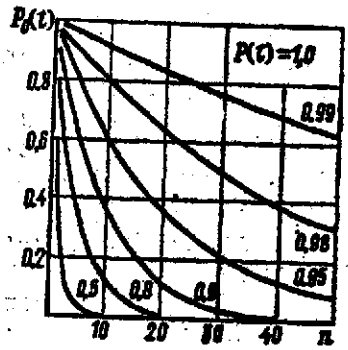

Fig. 8.1. Reliability of a system $P_0(t)$, consisting of sequentially connected elements with a reliability of each of P(t).

modern aviation piston engines, it has reached a value totalling 0.4-0.5 kg/hp. It is completely evident that such progressive development of basic operational characteristics of the machines makes provision of their reliability unusually complex and requires various additional expenditures. It must also be noted that the ever increasing rates of technological process will lead to a decrease in the "moral" service life of new equipment and, conseqently, in the cycles of its development and manufacture, this also cannot help but make the problem of increasing reliability more difficult.

The fourth reason is connected with peculiarities in the organization of modern planning and production on the basis of widely developed cooperation. Possessing tremendous economic advantages, cooperative production also makes problems of management, planning and control, including problems of reliability, more complex. Thus, for instance, the weight of finished products comprises an average of 30-35% of empty airplane weight and therefore the reliability of an airplane now depends on the airplane now building industry itself to a comparatively small degree (Fig. 8.2).

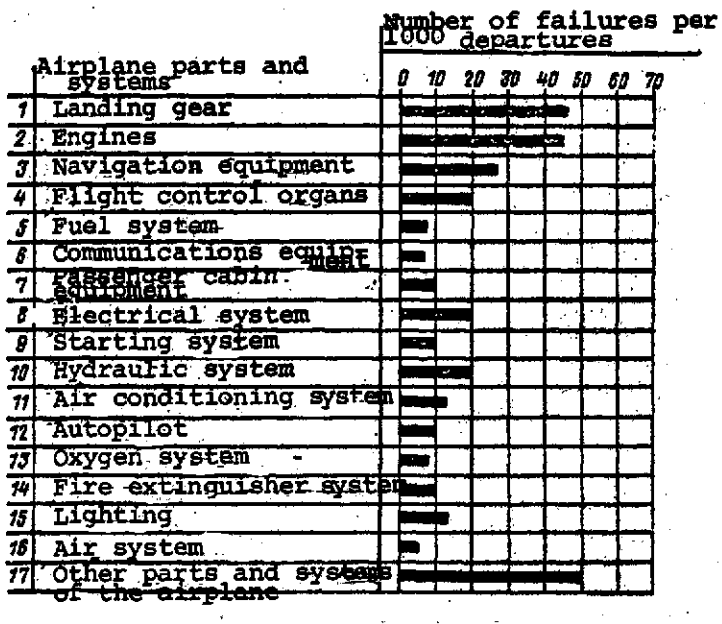

Fig. 8.2. Reliability of airplane parts and systems.

Finally, the fifth reason has a historical character and consists of the fact that the problem of reliability was until comparatively recently generally not seriously studied. Indices of reliability were not used for evaluation of industrial production and were not regulated. Moreover, increases in other indices such as cost and labor consumption were often achieved at the expense of reliability, since increasing production output is many times simpler than increasing its quality.

27.3. Meaning of the problem. Reliability is an inherent property of products, which characterizes, together with a number of other properties, their quality. With this, however, this characteristic of quality differs essentially from all the others. It is first of all necessary to note its special technical meaning, which is included in the following:

-- Reliability as a characteristic inherent in all products;

-- Differing from other indices of quality, reliability is connected with all the others and characterizes the manifestation of each of them;

-- If the machine does not possess the required reliability, its other properties cannot be utilized and, in essence, lose their practical value. In this sense, reliability is the main /287
characteristic of a machine's quality. While other indications of quality can be seen only as necessary ones, reliability, in provision of the required indications, is a sufficient condition of its high quality;

The value of reliability goes outside the framework of the problem of quality of separate machines. Insufficient reliability will lead to no achievement in a scientific and technical sense as a whole and becomes a barrier on the path of technical progress. On the other hand, to increase reliability itself, it is necessary to use all the leading scientific and technical achievements. Therefore, all the contemporary problems of scientific and technical progress are concentrated in reliability and it is responsible for their practical embodiment;

The problem of reliability acquires special meaning in the conditions of the ever increasing use of automation, which, in particular, is used during planning and production of airplanes, and chiefly, on athe airplanes themselves in the form of instruments, components and systems. Automatic flight control systems for STOL and VTOL airplanes and airplanes with LFC, as has already been noted, acquire special meaning.

The economic value of reliability is absolutely exclusive. Low product reliability will lead to a situation in which it is quickly removed from operation. This means that the economic ef- /288
fectiveness of its utilization will be sharply decreased and the labor expended on its manufacture is depreciated. It is appropriate to note that modern heavy passenger airplanes with a takeoff weight of 150-160 t cost no less than 6-7 million dollars (B-707, VC-10). Low reliability means colossal incidental losses at enterprises, connected with equipment stoppages, interruption of delivery times for required cargoes and so forth. In civilian aviation, this means a superfluous increase in the airplane fleet, deadline of unservicable airplanes and corresponding material losses. Low reliability in equipment means colossal additional expenditures on their servicing and repair. For instance, the cost of technical

servicing and repair of a passenger airplane exceeds its initial value by two to three times. The technical servicing and repairs of a motor vehicle exceeds its cost by seven times [68]. It should also be considered that reliability is the most important consumer property of any product. The safety and regularity of a transport means increase the influx of passengers and earning capacity of operations and vice versa. Thus, the accident of the "Comet" airplane in the beginning of the 1950's entailed total stoppage of ticket sales for these airplanes. A remark of one of the authors that achievement of reliability costs no small amount but its absence must be even more expensive is therefore absolutely justified.

Similarly to that which has been previously shown with respect to weight, aerodynamic quality and specific fuel consumption, it is possible to introduce the concept of "cost of reliability," i.e. the limiting value of feasible expenses on increasing an airplane's reliability per unit of measurement taken (see p. 212). Unfortunately, calculation of this index is very complex and corresponding satisfactory methods have not yet been found for it. However, it is absolutely not by chance that many authors see the increase in reliability of machine-building production as the most effective economic measure.

The problem of reliability in aviation also has an absolutely exclusive meaning because it is directly connected to the problem of safety. Safety of transport means is commonly evaluated with two indices (Fig. 8.3): number of casualties per one million passenger kilometers, and number of passengers per one million travel hours [85].

According to the first index, automobile transport in in first place (according to foreign data, 24 persons per billion passenger-miles). Airplanes are more than twice as safe as automobiles. However, buses and railroad transport are approximately 7-8 times safer than aviation. According to the second index, aviation is the most dangerous form of transport (2.4 persons per 1 million hours). It is 25-30 times more dangerous than buses and railway transport and 2.5 times as dangerous as automobile transport, it is absolutely evident that these evaluations are extremely imperfect. In particular, they do not consider the situation that /289 the passenger seating capacity of airplanes is always increasing and, consequently, the number of casualties belonging to each accident also increases. They also do not consider the possibility of losses, as the result of an airplane accident, of people not on board it (see also p. 115).

According to the means of providing it, reliability is first of all a technical problem, and according to results and consequences, it is positively an economic one. Additionally, it is impossible not to also see the important social aspect of this problem, since it places an impression on the rate and character of the development of

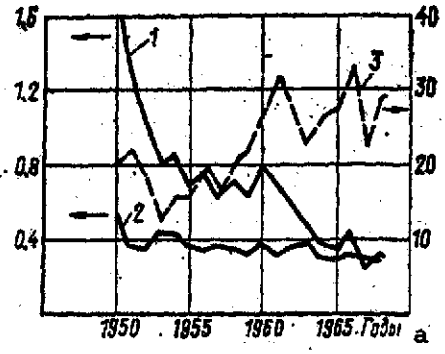

Fig. 8.3. Aviation safety (according to data of ICAO): 1. number of casualties per 100 million passenger-kilometers; 2. number of casualties per 100,000 flight hours; 3. number of casualties per accident.

Key: a. Years

production forces of society and largely depends on the relationship of people to their work.

In conclusion, it is appropriate to note that sometimes some aspects of the reliability problem (for instance, longevity) are seen as temporary ones, gradually losing their acuity. In support of this, arguments have been presented to the effect that acceleration of "moral" aging of equipment as a function of its progressive development somehow decreases the realness of physical longevity. This acceleration actually takes place. However, together with this, periods of obsolescence of equipment must always significantly exceed the periods of their physical longevity. Thus, for instance, successful aviation designs do not drop out of operation for 30-40 or more years (Li-2, Po-2). The period of physical longevity of an airplane determined by fatigue strength of the airframe is 20-30,000 hours, which corresponds to 10-15 thousand hours of flight operation. The growing roles of factors promoting a decrease in reliability of machines along with their development should also be considered (see p. 268). Therefore, the thesis that the acuity of the problem of longevity (and reliability) must decline with time is unfounded [68].

Chapter 28. Methods of Increasing Reliability /290

28.1. Stages of increasing reliability. The process of providing reliability has a constant character and continues at all stages of development and operation of the machines. The formula that the reliability of a product is compiled during planning, provided during production and supported during operation is generally known. This formula very successfully reflects the essence of the problem. The planning stage deserves special attention. Possible solutions at all succeeding stages depend on solution adopted here. Practice in the radio equipment industry shows, for instance, that 40-50% of equipment failures occur due to defects of a planning and construction character, 30% occur due to production reasons, and 20-30% occur due to mistakes in operation [67]. On the other hand, it is not necessary to think that the stages of production and operation have a secondary character in the problem of providing reliability. Certainly their possibilities are more limited. However, the most glittering achievements in

construction can be reduced to nothing by unsuccessful manufacture or careless operation. Therefore, the argument on the greater or lesser importance of one stage or another to a known degree is pointless. As was keenly noted in [67], it is similar to the argumentof to whom belongs the right of primogeniture: the egg or the chicken.

The theoretical bases and methods for increasing reliability at the planning stage are examined in detail below (see below). In this section, we will remain on the meaning of the production and operation stages.

From the production stage, a high state of the organization and technical art is required to provide product reliability, and namely: the use of modern technological processes and equipment; mechanization and automation of production; tuning of the production process; strict observation of established technology; proper content of equipment; modernplanning and production rhythms; including operations of running-in (burnishing) of the product in the production process; utilization of psychological and physiological means to improve working conditions (technical esthetics, lighting, etc.); a strict system of control, its automatization and use of progressive methods of control, for instance, statistical. Statistical control, as is known, allows analysis and adjustment of the course of the technological process and not only establishes the flaw but also reveals the reasons and prevents it. It is not difficult to note that specialized large-scale production has use of the most possibilities for fulfillment of the requirements of the state of the production and technological art listed above.

From the operational stage, strict fulfillment of instructions for operation, i.e., observance of periods and volumes of work on technical servicing and repairs, the use of high-quality lubrication and other materials, consideration of actual operating conditions, etc. is first of all required for provision and maintenance of product reliability. Practice shows that indices of reliability and longevity in machines, depending on the quality of their operation, can differ among themselves by 2-3 times [50]. /291

28.2. Theoretical bases of reliability. Increasing reliability of machines at the present time essentially depends on the development of the science of reliability and the introduction of its results into the practice of planning, construction and operation of the machines. The science of reliability was defined as an independent branch of knowledge comparatively recently and is still in the process of becoming. The creation of this science requires generalization and systematization of much widespread theoretical and experimental material, belonging to various areas of knowledge and is an extremely complex problem (Fig. 8.4). The science of reliability is compiled of the following parts: the physical-chemical theory of reliability; the mathematical theory of reliability; methods of constructing reliable machines; methods of

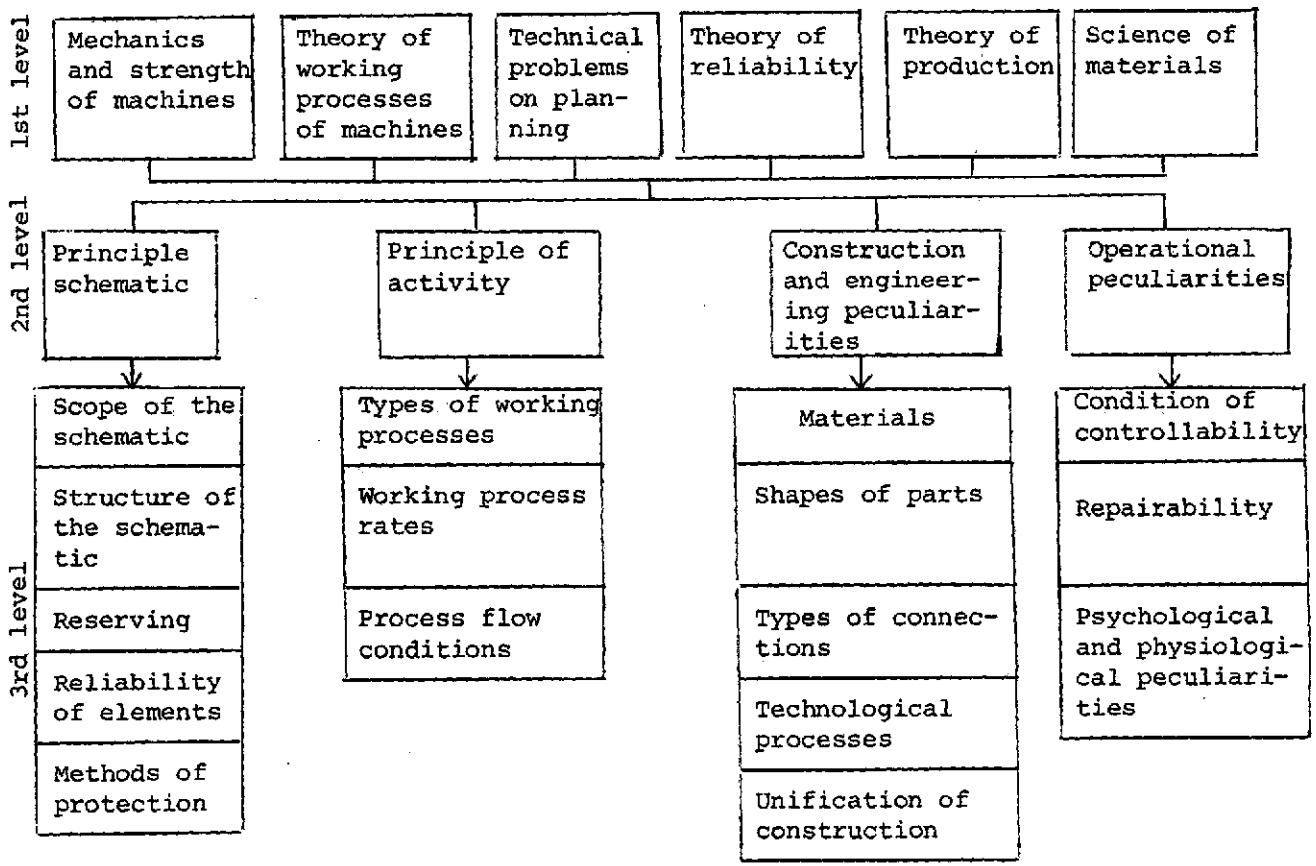

Fig. 8.4. Classification of reliability factors.

producing reliable machines; methods of operating machines; methods of experimental determination of reliability and the economics of reliability [21, 41].

The physical-chemical theory of reliability studies the nature of failures and breakage in machines, i.e. immediate causes of unreliability, such as wear, aging, fatigue, etc.

The mathematical theory of reliability is occupied with qualitative evaluations of reliability with statistical conformities of failures and, most of all, with methods of calculating the reliability of complex systems with set characteristics for its elements. This area of the science of reliability is based on conclusions of the theory of probability. The simplest examples of utilization of the mathematical theory of reliability are calculations of system reliability with the series and parallel connection of input elements. Thus, for instance, an electrical schematic consisting of series-connected elements fails upon failure of any of them. The reliability of this layout cannot be greater than the reliability of its weakest link, and falls with an increase in the number of these links (see Fig. 8.1). The probability of failure-free operation of such a schematic, consisting of n elements, connected in series, over time t is equal to $P(t) = e^{-\sum_1^n \lambda_i t}$. /292

With the parallel connection of identical elements, failure of any of them might only decrease the working capacity of the schematic, but not put it out of commission. The probability of failure-free work of a system of n elements connected in parallel over time t in the simplest case when failure of one of them does not effect the work of the others is equal to

$$P(t)=1-\prod_1^n \lambda_i t.$$

Methods of constructing reliable machines are based on the practical fractioning of the conclusions of the physical-chemical and mathematical theories with consideration of the problems of economics, technical esthetics, psychology and the general assumptions of the theory of construction.

The effect of properties of materials, technological processes, organization of production and other similar factors on reliability are examined in methods of production of reliable machines.

Methods of operation encompass problems of technical servicing, repairs and control over work of the machines.

The methods of experimental determination of reliability are devoted to problems of system modeling (mathematical, physical,

structural), bench tests and tests under actual conditions and, in particular, a very real problem at the present time -- accelerated testing.

Economics of machine reliability examines problems of the effectiveness of increasing reliability and allows solution of a number of important problems concerning optimization. The fact of the matter is that increasing reliability without a plan as an end to itself is unthinkable. Actually:

An increase in reliability is as a rule accompanied by an increase in the weight of the product, its cost and the cost of servicing and repairs, and an increase in the longevity of the product is limited to the period before its obsolescence; /293

If the total and between-repair resources, and also the periods of adjusting operations of products used as composite parts in any system do not agree among themselves, technical servicing of this system will be made extremely more complex, and high resources of some of its parts cannot be utilized.

Calculations of the optimal characteristics of reliability represent great complexity and, unfortunately, do not have a sufficiently well developed methodology up to the present time. Figs. 8.5 and 8.6 show, by way of an example, a diagram for accomplishment of some of these calculations.

The theory of reliability allowed establishment of actual means for increasing the reliability of products, which are based on analysis of corresponding causes of unreliability. The following classifications can be proposed for this analysis (see Fig. 8.4). Three levels of reliability factors should be differentiated. Factors of the first level have the most general character and form the theoretical fundamentals of the reliability problem as a whole. The technical problem occupies a special place among them. A literate composition of the technical problem must orient the developers as to the optimal characteristics of reliability, in particular, toward agreement of resources in the planned product with resources of that product for which it is intended. Factors of the second level unite related factors of the third level and, finally, factors of the third level include all actual reasons affecting separate partial types of reliability. /294

28.3. Services of quality and reliability. Besides the technical aspect, the organizational aspect also has an absolutely exclusive meaning in the problem of reliability. The direction of activity in planning, production and operation organizations in questions of reliability, i.e. transforming scientific and technical prerequisites into practical results, depends to a significant degree on the organization of their activity. The organizational aspect of the reliability problem comes down first of all to so-called quality control, which also include measures to increase

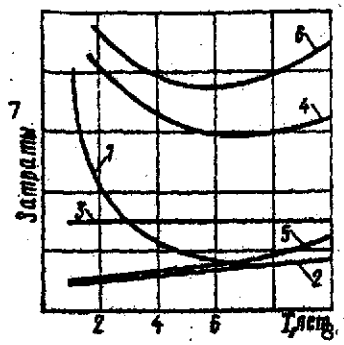

Fig. 8.5. Dependency of annual adjusted expenditures on machine resource T: 1. amortized deductions; 2. technical servicing and repairs; 3. fuel and incidental expenses; 4. cost of operation (sum of articles 1-3); 5. normative effect E_nK; 6. adjusted expenditures $C + E_nK$; 7. expenditures; 8. T, years

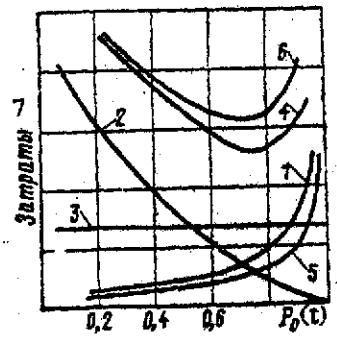

Fig. 8.6. Dependency of annual adjusted expenditures on probability of failure-free operation $P_0(t)$. Designations same as in Fig 8.5.

reliability [17]. In the governmental scale, quality control indicates the use of the system of following measures.

Scientifically based government norms of reliability indices. An example is the use of known norms for airplane airworthiness which are used in the majority of countries.

The organization of industrial and governmental overseeing on quality and reliability of production and stimulation of quality. An example might be plant and government testing of production, and also a system of quality indicators which are used in a number of countries: enterprises to which the right is given to place on their products quality indicators which testify to the fact that production corresponds to high national standards, have definite privileges.

The development of effective methods of evaluating, checking and controlling product reliability; planning by projecting and production enterprises of reliability indices in addition to other technical and economic indices.

Reflection of production quality in the pricing system and material stimulation of the enterprises for increased quality.

The economic basis for production quality, which must exclude certain of its errors including the position as if, due to economic feasibility considerations, the quality of products must force their state of technology and manufacturing periods to suffer.

Widespread development of unification, normalization and standardization binding together the best achievements in the area of quality and reliability.

Improvement of planning in the work of projection, production and operating enterprises.

Increasing the overall technical state of the art of enterprises, introducing leading technology and scientific forms of production organization.

Further binding and development of specialized productions, /295
which provides tuning and a high technical level of the processes of production and operation of products.

Widespread introduction of scientific methods of control and testing.

Scientific bases for quality control in our country were developed at several enterprises (the "Saratov," "Gor'kiy" system and others) and received general recognition, including some from abroad. Specifics of the reliability problem require, however, creation of specialized reliability services in addition to quality control. (Suffice it to say that control of reliability differs in principle from control of other product qualities.) These services are now being created in many organizations.

Chapter 29. Planning Reliable Machines

29.1. Principle perfection of machines. The perfection of machines, based on changing layout, principle of its operation or working rates is the most important method for increaseing reliability and has been named principle perfection by us.

1. The layout of a product characterizes the scope and structure (i.e. the quantity of elements and their interrelationships). For greater reliability, the scope of the layout must be, as was already shown earlier, as small as possible, as the simpler layouts are usually also the most reliable ones. Monolith panels, soldered pipes or printed electrical circuits are more reliable than multi-part systems with a large number of connections. Installation of a starter or generator on an engine shaft is more reliable than the traditional external layout of location with a drive through a system of shafts and conic gears.

The principle of unitizing structures, i.e. combining and isolating elements which perform a closed set of functions into single easily-removable and repairable units, is highly promising with respect to simplifying schematics. Unitization (blocking) essentially decreases the number of parts and dimensions and is used in the structures of engines and systems of an airplane.

The structure of a schematic is basically characterized by the type of interconnections (junctions) of its elements. Series and parallel connections should be differentiated. The most important principle of increasing the reliability of all structures, duplication (reserving) with different degrees of multiplicity, is based on the property of parallel connections, of which was spoken about

above. It has become common to duplicate engines, landing gear wheels, electrical circuits, control systems and load-bearing elements of the structure in airplanes. (On the effect of the number of engines on reliability, see Chapter 7.) The statically undefined character of aviation structures in the majority of cases makes for multiple duplication of load-bearing elements. Duplication is very widely used in radio and electronic components. Generaly and separate (local) duplication should be differentiated. In the first case, the entire system is reserved (for instance, double controls on the airplane), and in the second, only certain, weaker or more essential of its links (for instance, wheels on the landing gear, certain sections of the electrical circuit and so forth) are duplicated. Separate duplication is naturally more economic. "Cold" and "hot" duplication are also differentiated. In "cold" duplication, the spare element begins to work only upon failure of the main one. Many emergency systems often work on this principle. With hot duplication, several mutually duplicated elements work simultaneously, but at reduced working rates. Upon failure of any of them, the remaining ones continue to work at an increased rate Examples of hot duplication are the multimotored systems in airplane, multiwheeled gears and others. Synchronization of the work of propellers and engines in STOL and VTOL airplanes are a characteristic example of this duplication. The installation of several engines on airplanes of these types frequently still cannot provide the required reliability, since upon failure of one or more of them, high unbalancing forces can arise. Hot reserving is a more economic system than cold, and is used more often. /296

The most perfect forms of duplication have been developed by nature, and, in particular, are embodied in the nervous system of man [10, 36]. Biological duplication is based on two basic principles, which have already begun to be used in technology: functional substitution, rebuilding and self-instruction; and combination of several duplication forms of a different level: total and partial. The first principle consists of a situation in which upon failure of any system, others, without being adapted to it previously, can take over the function of that failed system. The second principle indicates that the reserve elements or systems must function in exactly the same way as the failed ones. They can be significantly simpler and perform only partial, approximate reserving.

Methods of reserving have a huge meaning and widespread usage in technology, it is impossible, however, not to note that they are polliatives and testify to the insufficient reliability of elements of the structure. It is not by chance that they are called methods of creating reliable structures out of unreliable elements. Reserving usually causes an essential increase in complexity, weight and cost of the product. True, under contemporary conditions, failure to duplicate and increase reliability in elements can in a number of cases prove to be even less advantageous. /297

Besides reserving, increasing the reliability of schematics can also be achieved by equalizing the reliability of its separate components through installation of principally more reliable structures in narrow places. This system of increasing reliability can be called qualitative reserving or providing equal reliability. Since there are always certain weak places in actual structures, this method can be extremely effective. However, from the point of view of saving weight or cost of the product, in a number of cases less reliability for its less essential parts can be admitted. For instance, in airplane building, the safety margin in calculating for strength is taken to be within the range of from 1.5 to 2.0, depending on the responsibility of the given component. For the purpose of decreasing the weight of the airplane, a differentiated designation of this margin might be justified for certain parts and elements inside each component.

Along with reserving, the method of protection has a great practical meaning. Means of protection are extremely varied. Dampers and shock absorbers are used to combat dynamics. Thus, the airplane landing gear is a damper for the airplane structure. Cushioning equipment is widely used. Shock absorbers, dampers and flexible sleeves are widely used in airplane mechanisms. Electrical circuits are protected from current short circuits by special automatic devices (mechanical types of protection are used in the forms of jackets, guards, limiters and so forth). Protection elements also include various signals and the emergency lifesaving means used on airplanes.

The problem of finding the optimal layouts of a product according to their nature of a calculated character is also solved by the ways of the mathematical theory of reliability. In solution of these problems, one often looks at such variations as, for instance:

Minimum weight with set cost and reliability;

Maximum reliability with set weight and cost.

The solution of similar optimal problems is accomplished with the same means, which were examined above (Chapter 5).

2. The principle of operation of machines is characterized by the working processes used in them and their working rates, which, according to their very nature possess different degrees of reliability. Thus, the mechanical control of an airplane is more reliable than hydraulic and electrical. Pyrotechnical devices are more reliable than pneumatic and hydraulic ones. Semiconductor devices are more reliable than similar lamp ones (the period of failure-free service in them is 60-70 times greater) Roller bearings are more reliable than friction bearings. An airplane with a normal takeoff system is more reliable than a VTOL airplane and so forth. It is important to emphasize that reliability in this /298
aspect has a character set by history and these evaluations must be changed with time.

3. Operating rates are evaluated by the amount, equality and the sign of loads and by working conditions. The lower the load level, the more reliable the work of the machine. Thus, for instance, it is known that an airplane's airframe possesses high reliability in comparison with its other parts. This is explained by the fact that the average level of stress in the airframe structure corresponds to an operational overload of $n^o = 1$, while the construction material is selected based on possible brief loads with which overload reaches a value of 2.5-3.5. In exactly the same way, low current density in the electrical wiring will lead to an increase in its reliability. At the present time, the question of increasing the life of the main engines of an airplane up to the life of the airframe by eliminating the high takeoff power setting and using special booster engines on takeoff is being considered. Weight and economic analysis points to the feasibility of a similar solution [56].

Equality in a working process of a product is evaluated with the level of dynamic loads (peak loads in electrical or hydraulic systems). Thus, a turbojet engine is more reliable than a piston one due to the fact that a motion of a rotary character takes place in it instead of the back-and-forth one.

Limitation of changing sign loads, which cause the fatigue phenomenon and the provision of favorable conditions for the work of a machine and its parts (temperature, lubrication, harshness of medium and so forth) have a great meaning for providing reliability and longevity in machines. Thus, for instance it is known that high quality lubrication increases the life of mechanisms by double.

29.2. Construction, engineering and operational improvement of machines. Tremendous reserves for increasing reliability are laid into the construction and engineering peculiarities of machines, which depend on the properties of the structural materials, the shapes of the parts, the methods of their machining, types of connections, etc. High-quality steels and alloys as a rule allow a sharp increase in the reliability of parts manufactured of them. Decreasing the weight of these parts further promotes an increase in reliability, since it leads to lower loads (mass forces, contact loads). Synthetic and composition materials, with which it is possible to obtain special, desirable sets of properties, open up special possibilities in the area of reliability. Materials should be properly used. For instance, aluminum alloys of the type B-95, which are strong but less resistant with respect to fatigue, should not be used for tension elements of construction. Analysis of the problem also shows that the traditional practice of using materials /299 which are cheap and effective from an engineering point of view at the expense of product quality is as a rule economically unfeasible.

A significant increase in the fatigue life of parts is achieved by means of decreasing stress concentrations through such means as:

-- The use of corresponding shapes of parts with a smoothly changing section, smoothing of edges, central transmission of forces and so forth;

-- Providing cleanliness and protection of the surfaces from corrosion;

-- The use of bonding, welding and soldering instead of riveted and threaded connections. Thus, for instance, it has been established that 60% of the failures in airplane hydraulic systems were caused by leaking in a connection fitting. Reliability of the system is sharply increased (and weight is decreased) if threaded and hose pipe connections are replaced with soldered ones;

-- Provision of precise and tight fit in connecting parts without excess interferences, and the use of damping washers, seals, putty and so forth in connections;

-- The use of three-ply structures.

Increasing parts' resistance to wear is achieved by means of using connections with multiple roots of force transmission (splines, tooth sleeves, etc.), replacing friction pairs with and; special preparation of wearing surfaces. The surface layers of parts are usually loaded more highly than internal ones, due to the appearance of flexion or torsion, which occur even during transmission of the simplest types, deformation or due to contact loads. The reliability of these parts is increased with special surfacing, nitriding, chroming or special machining of the surfaces (rolling, shot peening, stamping and others).

The unification of the parts of a machine and its larger forms: normalization and standardization have a large meaning is this problem. Unified elements are as a rule produced under conditions of a higher technological level of production, which promotes an increase in reliability.

The operational peculiarities of a machine characterize its adaptability to providing reliability in the process of operation. This adaptability is basically conditioned by repairability and psycho-physiological features of the machine. The most important property of a machine in the first aspect is the possibility and convenience for monitoring its condition. Not one product can be considered reliable if this possibility is not provided. The highest forms of control are automatic control, which is accomplished with automatic devices and automatic built-in control, where the controlling devices are included in the structure of the product and not only signal upon failure but warn of its possibility beforehand. At the present time, these systems have begun to be used in airplane equipment. Specialists think that built-in automatic control will become an inherent part of all transport means in the near future [9]. Systems which will also be capable of performing

/300

automatic repair will apparently be created in the future. Another important index of the repairability of a machine is the principal possibility of its technical servicing and repair. And finally, the third feature of a product in this plane is the adaptability of its structure to the most progressive forms of servicing and repairs, which require minimum expenditures in time and labor. This adaptability is provided by, for instance, the following means:

Agreement of reliability indices in all elements of the structure, which allow effective accomplishment of servicing and repair in planned adjustment periods according to a system of planned preventive maintenance repair, and not upon demand. (True, in some cases, for instance in the presence of perfected types of automatic control, the system of repair upon demand might prove to be more economic (2.6). However, agreement of reliability indices will in all cases remain feasible);

Interchangeability of structural elements, possibility of using spare parts, use of a system of repair dimensions allowing replacement of worn parts with others of a larger dimensions, without destroying the parameters of the working process;

Use of a system of repair parts, components and units, allowing repair to be accomplished by means of rapidly replacing whole parts of the machine (with their subsequent repair in stationary positions);

Use of a system of constant maintenance, allowing all types of maintenance (on-going and measured) to be performed by means of constantly sequentially renewing separate parts, components and units of the machine without removing them from operation.

The psycho-physiological features of a machine form a set of properties on which the "man-machine" contact depends during the process of its operation. The problem of this contact is being studied by relatively young sciences, technical esthetics, engineering and industrial psychology, and ergonomics.

The character of the activity of a person (in particular, the pilot) is determined by, for instance, such factors as: comfort of the operator's seat, the positions of arms, legs and so forth; the general esthetic perception of the cabin, controls, instruments and control organs which depend on their color and construction; the quantity and arrangement of instruments and control organs, the shape of control organ handles, loads experience by the person in the process of control and so forth.

29.3. Planning the reliability characteristic. Three methods/301 have been developed in practice for determining the planning characteristics of a machine's reliability. The method of refinement, the method based on the principle of "safe service life" and the calculation-experimental method.

The method of refinement consists of monitoring the behavior of the machine during the process of its operation and gradually eliminating defects arising during this. This relatively primitive method appeared earlier than the others. It was based on the erroneous point of view that reliability of a product can be determined and moreover increased only during the process of its operation, according to how much factual material is accumulated, and that determination of reliability and the planning stage is either impossible or unfeasible, since lengthy testing and great expenditures are required. The method of refinement is the most convenient for machine manufacturers, but places operators in an exclusively serious position. At the present time, it can be considered proved that expenditures on increasing machine reliability during the process of its planning comprise an insignificant portion of those losses which arise during operation due to its lack of finish. Therefore, the method of refinement, which has received the accurate name "experimentation on the consumer" should be recognized as unscientific and basically faulty [48].

The second of the methods named above consists of establishing the period of safe service, during which it will work with sufficiently guaranteed reliability for each product on the basis of statistical data. Upon expiration of this period the product is written off and removed from operation, regardless of its actual condition. This method is based on the principle of insurance and is connected with such negative consequences as overweighting of the structure and losses from writing off machines which are as a rule still in servicable condition. Naturally, this methods is also not scientific.

The scientific method at the present time is the calculation-experimental one. It includes theoretic calculation of the characteristics of reliability and their experimental checking as a whole during the process of the machine's planning. The calculations in this are based on scientific propositions on reliability. Experimental checking is accomplished on models, mock-ups, benches and by means of testing prototypes. Modeling, mocking-up, bench testing and full-scale testing are included in the leading contemporary means for increasing machine reliability and are a necessary addition to calculations. They allow the conduct of investigations on a wide front and provide a significant savings in time and expenses.

The calculation of reliability characteristics of a new product must be based on information on the reliability of similar existing structures. The data shown in Fig. 8.2 can serve as an /302
example of this information as it applies to airplane. A reinforced determination of the reliability characteristics of a new airplane is accomplished immediately with these data. For this, the actual features of its construction and the construction of prototypes should be compared. A more accurate solution of this problem is based on comparison of the structural diagrams of the product's

reliability, which described the interconnection between all of its elements. Knowing the reliability characteristics of elements and using equations of the mathematical theory of reliability, it is possible to calculate the reliability characteristics of the product. Fig. 8.7, as an example, shows the structural schematic of the reliability of an airplane's landing gear [84].

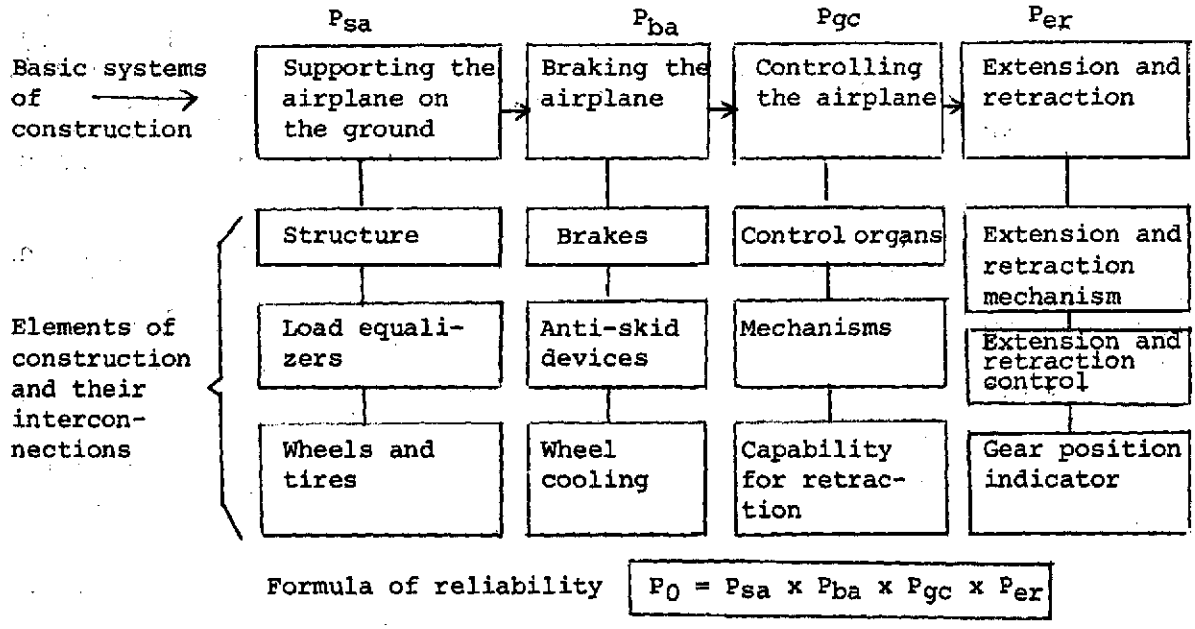

Fig. 8.7. Block diagram for calculating reliability of landing gear

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